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Molten Salt Destruction of HCB (Hexachlorobenzene) and Chlordane Bench and Pilot Scale Tests

Rockwell International, Canoga Park, CA

Prepared for

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September 1984

MOLTEN SALT DESTRUCTION OF HCB AND CHLORDANE - BENCH AND PILOT SCALE TESTS

by

S. J. Yosim, L. G. Kellogg, S. Sudar
Energy Systems Group
Rockwell International

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Contract No. 68-03-3014, Task 21

Project Officer

Richard A. Carnes
Incineration Research Branch
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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16. ABSTRACT

A research test program to demonstrate the destruction of chlorinated materials by the Molten Salt Destruction (MSD) process was conducted. In this process, combustible material and air are continuously introduced beneath the surface of a sodium carbonate-containing melt at 900-1050°C. Any acidic gases such as HCl produced from chlorinated organic compounds are neutralized and retained in the melt. The chlorinated materials tested were solid hexachlorobenzene (HCB) and liquid chlordane. The HCB was a simulant for PCBs and the chlordane was representative of liquid chlorinated industrial wastes. The overall objective of the test series was to provide molten salt process performance data and to challenge the molten salt process limits for adequate waste destruction. The program consisted of bench-scale and pilot-scale tests. Both destruction efficiencies (DE) and destruction and removal efficiencies (DRE) were determined.

The federal standards for thermal process destruction of PCBs of 99.9999% destruction and 99.99% destruction for halogenated organics such as chlordane were met in both the bench-scale and pilot-scale tests.

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FOREWARD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environments and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report presents the results of a test program designed to evaluate the destruction of chlorinated organic materials by the Molten Salt Destruction (MSD) process. Destruction of solid hexachlorobenzene (HCB) and liquid chlordane was evaluated in bench-scale and pilot-scale facilities of Rockwell International, Inc., the developer of the process. The Molten Salt Destruction process involves injection of waste materials and oxygen or air into a reactor containing molten carbonate salts at temperatures between 1600°F and 2000°F. This study concluded that high destruction and removal efficiencies performance (greater than 99.9999 percent) is possible in most cases for HCB and chlordane.

Further information on this subject may be obtained from the Incineration Research Group, Energy Pollution Control Division, IERL-Ci.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

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ABSTRACT

A research test program to demonstrate the destruction of chlorinated materials by the Molten Salt Destruction (MSD) process was conducted. In this process, combustible material and air are continuously introduced beneath the surface of a sodium carbonate-containing melt at 900-1050°C. Any acidic gases such as HCl produced from chlorinated organic compounds are neutralized and the neutralized products are retained in the melt. The chlorinated materials tested were solid hexachlorobenzene (HCB) and liquid chlordane. The HCB was considered to be a simulant for PCBs and the chlordane was representative of liquid chlorinated industrial wastes. The overall objective of the test series was to provide molten salt process performance data and to challenge the molten salt process limits for adequate waste destruction. The program consisted of bench-scale and pilot-scale tests. Both destruction efficiencies (DE) and destruction and removal efficiencies (DRE) were determined.

The federal standards for thermal process destruction of PCBs of 99.9999% destruction and 99.99% destruction for halogenated organics such as chlordane were met in both the bench-scale and pilot-scale tests.

Bench-Scale Tests — The bench-scale tests generated a data base for the subsequent pilot-scale tests. The DE and DRE of HCB exceeded 99.9999% at 900-1000°C. A lower value (99.87%) was obtained at 800°C. This may indicate a lower temperature limit to the process. The HCB concentration in the spent melt was <0.001 ppm. The DE and DRE for chlordane were >99.99986 and >99.9999%, respectively, with excess air. With deficient air (81% of stoichiometric air), the DE and DRE were >99.99% based on the GC peaks which had the same retention time as those of the chlordane standard. However, the peaks, when examined by GC-MS, were found to be due to species other than chlordane. The concentration of chlordane in the melt was <0.01 ppm. The HCl concentration in the off-gas was <100 ppm. No Cl_2 or phosgene was detected in the off-gas (<0.3 ppm).

Pilot-Scale Tests — Based upon data generated by bench-scale tests, the pilot-scale tests were planned and conducted. The tests demonstrated excellent destruction of HCB and chlordane. The DRE of HCB due to the molten salt destructor alone exceeded 99.9999% in all cases. In some tests, the DRE exceeded 8-9's (99.999999%). The DRE for the entire system including the baghouse exceeded 9-9's in all tests. The concentration of HCB in the melt was ≤0.1 ppm. In the case of chlordane, the DEs were >99.996% in three tests and 99.9998 and 99.99994 in two other tests. The DRE due to the molten salt alone exceeded 99.9999% in all cases but one in which the DRE was 99.99983. In two cases, it exceeded 7-9's. The DRE for the entire system exceeded 7-9's in all tests. The chlordane concentration in the melt was <1 ppm. The HCl concentration in the off-gas was <100 ppm. The NO_x concentrations in the

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off-gas were in general ≤ 125 ppm. The particulate loadings downstream of the baghouse were very low (<50 mg/m^3).

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ABBREVIATIONS

DE - destruction efficiency

DRE - destruction and removal efficiency

EMSC - Environmental Monitoring and Services Center of Rockwell International

GC - gas chromatograph

GC-EC - gas chromatograph-electron capture

GC-MS - gas chromatograph-mass spectrometer

gr/scf - grains per standard cubic foot

HCB - hexachlorobenzene

HEPA - high efficiency particulate absolute

MSD - Molten Salt Destruction

MSTF - Molten Salt Test Facility

PCB - polychlorinated biphenyl

PFP - polyurethane foam plug

PICS - product of incomplete combustion

POHC - principal organic hazardous constituent

ppmv - parts per million by volume

ppmw - parts per million by weight

RCRA - Resources Conservation and Recovery Act

RIC - reconstructed ion chromatography

TSCA - Toxic Substances Control Act

W_{in} - mass feed rate of the principal organic hazardous constituent into the thermal destructor

W_{out} - mass rate of the principal organic hazardous constituent exiting the thermal destructor

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SECTION 1

INTRODUCTION

The resolution of problems associated with the management of hazardous waste is important to public health and safety. Action by local, state, and federal agencies in response to expressed public concern has stimulated the industrial and technical community to undertake significant waste management efforts. Some of the conventional methods previously believed acceptable for treating these wastes have subsequently proven to be unacceptable. Thus, alternate methods and particularly those that assure complete and safe waste destruction as opposed to land burial, surface impoundment conventional incineration, etc., are being investigated. An alternate method that shows promise for efficient waste destruction is the Molten Salt Destruction Process (MSD).

MOLTEN SALT DESTRUCTION PROCESS

The MSD process is based on the use of a molten turbulent bed of salt, such as sodium carbonate, as a heat transfer and reaction media. In this process, combustible waste and air are continuously introduced beneath the surface of the molten salt which is nominally at atmospheric pressure and at 800-1050^{o}C (1470-1920^{o}F). The air is injected at a high velocity to promote turbulence. The combustible material is added in such a manner that any gas formed during combustion is forced to pass through the melt before it is emitted into the atmosphere. The off-gas containing carbon dioxide, steam, nitrogen, and unreacted oxygen is cleaned of particulates in commercial applications by passing it through a baghouse. A schematic of the molten salt destruction process is shown in Figure 1.

Acidic gases, such as HCl and SO_2, produced from halogenated organic compounds and sulfur-containing organic compounds, respectively, are neutralized

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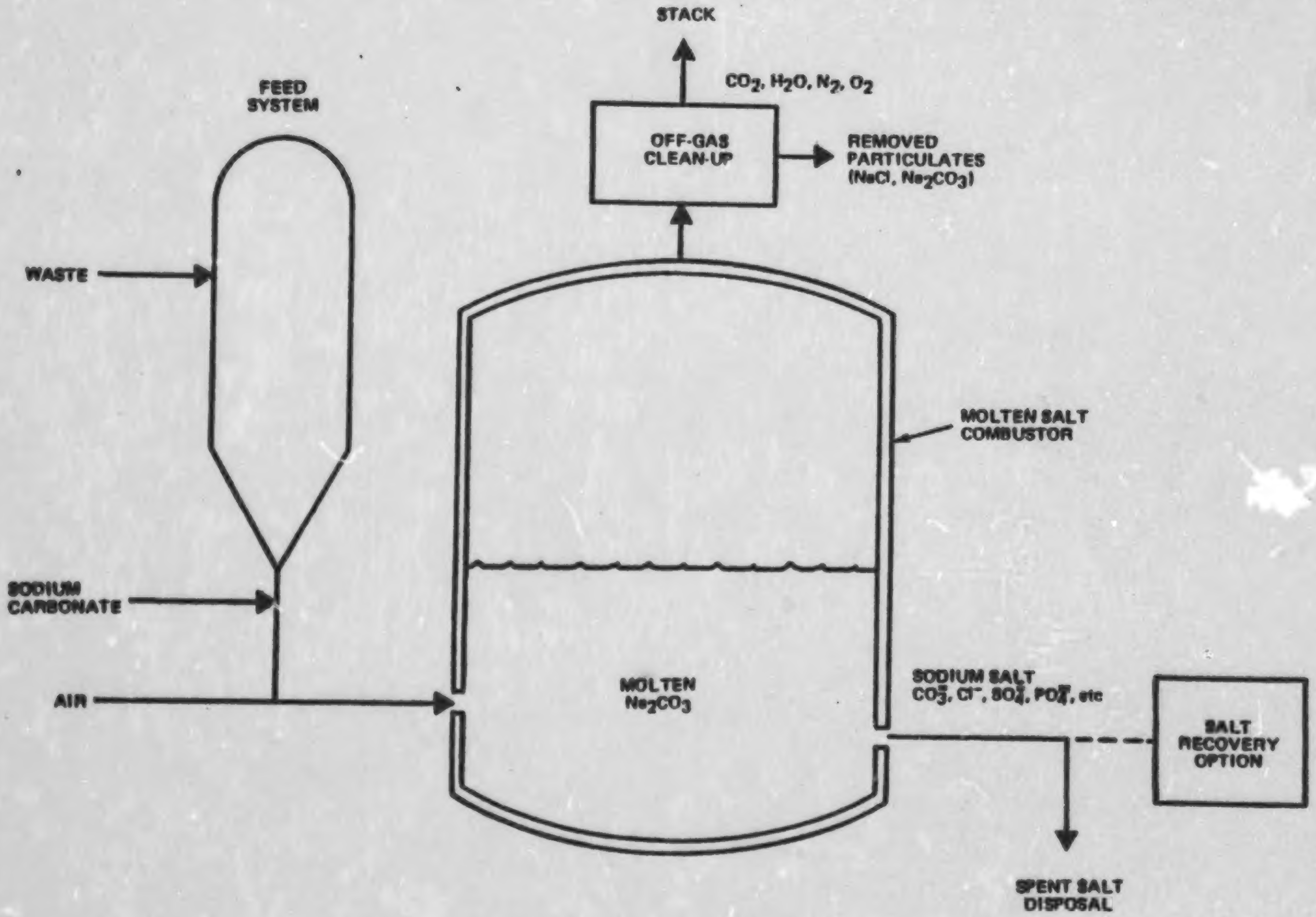
STACK
CO_2, H_2O, N_2, O_2
FEED SYSTEM
OFF-GAS CLEAN-UP
REMOVED PARTICULATES ($NaCl$, Na_2CO_3)
WASTE
MOLTEN SALT COMBUSTOR
SODIUM CARBONATE
AIR
MOLTEN Na_2CO_3
SODIUM SALT $CO_3^=$, Cl^-, $SO_4^=$, $PO_4^{\equiv}$, etc
SALT RECOVERY OPTION
SPENT SALT DISPOSAL

Figure 1. Schematic of Molten Salt Combustion Process

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and the neutralized products are retained by the alkaline Na_2CO_3. The ash introduced with the combustible waste is also retained in the melt. The char from the fixed carbon is consumed in the salt. The temperatures of oxidation are too low to permit a significant amount of NO_x to be formed by fixation of the nitrogen in the air.

Inorganic products resulting from the reaction of organic halides, sulfides, etc., with sodium carbonate build up in the melt and must be removed at some point. This is to prevent complete conversion of the sodium carbonate with an eventual loss of the acid pollutant removal capability. The concentration of halide salt, sulfate salt, or ash that is in the sparged salt bed is controlled by either continuously injecting additional sodium carbonate and overflowing the bed or by fill/drain batch operation of the destructor vessel. The salt withdrawn through an overflow duct is essentially a uniform mixture of reacted and unreacted salts due to the homogenizing action of the high-velocity injection of combustion air beneath the surface of the bed. Intermittent "batch" overflow may also be used with continuous sodium carbonate injection. The method of destructor operation (batch, semibatch, or continuous) is dependent primarily on the composition and rate of the waste feed. When feeds have a large fraction of inorganic elements (halides, sulfur, ash, etc.), the destructor is operated with continuous salt injection and overflow. When feeds have a small amount of inorganic elements or when the feed rates are low, the destructor is operated with batch drain.

The amount of air injected into the bed is controlled to produce a specific superficial gas velocity through the melt. Generally, the higher the permitted superficial gas velocity, the higher the waste product throughput of the destructor. Too high a velocity results in excessive melt entrainment into the off-gas piping and potential bypassing or poor bed contact of the injected material. For waste disposal, a superficial velocity of 0.76 m/s (2.5 fps) has been selected as a conservative operating condition for a large-size unit.

The sodium carbonate used as the active salt bed component was selected because it is compatible with the combustion products, CO_2 and H_2O, and

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because it reacts with acidic gases such as HCl produced from organic chloride compounds. It is also relatively inexpensive, non-toxic, stable, and non-volatile.

Thermal control of the salt bed is maintained by a combination of means. These include (1) addition of auxiliary fuel to waste feeds with low heating value, <10,470 kJ/kg (<4500 Btu/lb), (2) cooling of the outside surface of the metal destructor vessel with forced air, (3) salt recycle, and (4) adjustment of the combustion air feed rates. The primary means are fuel addition for wastes with low heating values and forced air cooling for wastes with high heating values.

The spent salt which is non-hazardous is soluble in water. It, therefore, must be disposed of in a controlled or impermeable landfill.

In summary, the MSD process provides for efficient waste destruction through intimate mixture of the waste stream with highly reactive alkaline media comprising the high-temperature sodium carbonate and combustion air.

HISTORICAL BACKGROUND

A study of molten carbonate technology for pollution control was initiated in the late 1960's. In addition, an extensive investigation of molten salt chemistry was conducted by the Rockwell research staff under contract to the Atomic Energy Commission. This investigation consisting of a basic research program, which included studies of the thermodynamic and transport properties of molten salts, was conducted between 1956 and 1970.

A company-funded program in 1969 demonstrated the potential of the molten salt (sodium carbonate) combustion process for resource recovery from waste products such as municipal and industrial waste and agricultural residues. The recovery of silver from X-ray film and the gasification of organic waste materials by submerged, partial combustion in a molten salt bed were achieved in laboratory-scale tests. Subsequent studies were made to demonstrate the

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capability of the molten alkali metal carbonate salt to retain acidic reaction products such as hydrogen chloride and sulfur dioxide from submerged combustion of pesticides.

Ensuing application studies of the molten salt combustion process were conducted in bench-scale and/or pilot-scale tests during the 1970's. These applications included the volume reduction of low-level radioactive wastes; the destruction of chemical warfare agents such as GB, VX, and mustard gas; the destruction of a variety of organic chemical waste materials including pesticides and halogenated organics; and the clean gasification of high-sulfur coal to generate low-Btu gas. The waste materials treated in bench-scale tests with molten salt are listed in Table 1. Destruction efficiencies of 99.99 to >99.9999% were measured for the toxic and hazardous waste materials. The gasification of coal was conducted in a DOE-funded Process Development Unit capable of processing 1,000 kg/hr of coal. This data was reported to the DOE Project Office, Fossil Energy Division, Morgantown, West Virginia.

Although the extensive series of tests performed in the 1970 decade demonstrated the feasibility of broad application of the molten salt process to toxic and hazardous waste control, several development tasks remained as of 1980 before commercial application could be achieved with sufficient confidence in the system's performance and economic competitiveness. These tasks included:

1) The development of a low-cost metal containment material for molten salt to replace the high-cost high-purity alumina refractory utilized for the development and feasibility tests.
2) The development of reliable solid and liquid feed systems.
3) The increase of waste throughput to optimize the system economics.
4) The development of a reference commercial MSD plant design and analysis of its economics.
5) The verification of high destruction efficiency of hazardous materials such as chlorinated organics on a pilot-scale level. (All the materials in Table 1 were tested only on the bench-scale level.)

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TABLE 1

HAZARDOUS MATERIALS DISPOSED OF IN MOLTEN SALT DESTRUCTION BENCH-SCALE TESTS

Toxic Chemical Agents

- GB
- VX
- Mustard
- Lewisite
- Detoxified GB, Mustard, and Phosgene

Pesticides

- DDT
- Malathion
- 2,4-D

Chemical Wastes

- PCB
- Perchloroethylene Bottoms
- Trichlorethane
- Chloroform
- Diphenylamine HCℓ
- Monoethanolamine
- Nitroethane
- Para-arsanilic Acid
- Cyanide-Containing Wastes

Combustible Waste from Nuclear Plants

- Tributyl Phosphate
- Ion Exchange Resins
- Silicon Carbide
- Leaded Gloves
- Aqueous Solutions
- Organic Solids Containing Plutonium

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6) The definition of process variable limits for safe and reliable MSD system operation.

Tasks 1 through 4 above have been the subject of company-funded research and development programs conducted in 1981. A commercial metal alloy for molten salt containment has been satisfactorily demonstrated for excess air and low sulfur applications. Solid and liquid feed systems for bulk materials have also been successfully tested. The use of oxygen-enriched air for combustion has permitted a 3:1 increase in waste throughput for a given size destructor vessel. A reference plant concept design has been completed; it is the basis for current marketing of the MSD system.

Tasks 5 and 6 are the subject of the current EPA funded program. The Task 6 development area is also being addressed in separate company- and industry-funded programs. Process variable limits are being investigated in these programs for MSD treatment of hazardous wastes other than chlorinated organics.

CURRENT PROJECT

The Energy Systems Group (ESG) of Rockwell International conducted a research test program to demonstrate the destruction of chlorinated organic materials using the Rockwell Molten Salt Destruction (MSD) Process under Contract 68-03-3014, Task 21, for the U.S. Environmental Protection Agency (EPA), Cincinnati. Two chlorinated materials were selected for destruction:

1) Hexachlorobenzene (HCB), a solid, and
2) Chlordane, a liquid.

The HCB is considered to be a simulant for polychlorinated biphenyls (PCBs); the chlordane is representative of liquid chlorinated organic industrial wastes. The waste management of PCB is controlled under the Federal Toxic Substances Control Act (TSCA, 15 USC 2601, Public Law 94-469). The disposal of chlordane and all hazardous materials, exclusive of PCB, is regulated under the Resource Conservation and Recovery Act (RCRA).

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The PCB regulations (40 CFR 761) implement provisions of TSCA; Subpart E, Annex I specifies operating requirements for high-temperature incinerators used for PCB destruction, namely, 1200°C and a residence time of 2 seconds.(1) The PCB regulations do not require calculation of destruction efficiency.(2) Instead, they require that PCB emissions to the air not exceed 1 mg per kg of PCBs fed (when burning non-liquid PCBs only). They also require that the process residues contain less than 50 ppm PCB. However, destruction efficiencies are calculated and reported herein because it is a widely used figure of merit and because it will enable the environmental community to compare present with past thermal process results. Destruction efficiency (DE) is calculated using the following equation:

6-1/2

$$DE = 100X \frac{W_{in} - W_{out}}{W_{in}}$$

9-1/8

where W_{in} is the mass feed rate of the principal organic hazardous constituent (POHC) into the thermal destructor (kg/h) and W_{out} is the mass rate of the POHC exiting the thermal destructor (kg/h). In this report, W_{out} will include the POHC exiting with the spent melt, the particulates and the off-gas.

Chlordane was selected as a typical waste covered by RCRA regulations.(3) According to this regulation, a destruction and removal efficiency (DRE) of 99.99% must be achieved. The DRE is calculated using the same equation except in this case W_{out} is the mass emission rate of the POHC present in exhaust emissions prior to release to the atmosphere. Thus, in contrast to DE, W_{out} does not include the POHC exiting with the spent melt or with the particulates.

It is to be noted that although the MSD process is a thermal process, it is not an incinerator in the conventional sense. Its performance is measured, for the purpose of this study, on the basis of the regulations that are being applied to incinerators under TSCA and RCRA.

The overall objective of the test series was to provide molten salt process performance data and to challenge the molten salt process limits for

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adequate waste destruction. Testing was conducted using both bench-scale and pilot-scale sized process equipment. This report describes the test program, test results and correlation of the two sets of test data obtained with the bench-scale and pilot-scale equipment. Both destruction efficiencies, and destruction and removal efficiencies are reported for the HCB and chlordane tests.

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SECTION 2

RESULTS AND CONCLUSIONS

RESULTS

Bench-scale and pilot-scale tests of the Rockwell Molten Salt Destruction process with hexachlorobenzene and chlordane achieved the following results:

1) The destruction efficiency (DE) and destruction and removal) efficiency (DRE) of HCB were >6-9's 00* in the bench-scale tests at the temperature range of 900-1000°C.
2) The DE and DRE of chlordane were >5-9's 86** and >6-9's 03 for chlordane in the bench-scale tests at 900-1000°C and with excess air.
3) The HCB DE achieved by the molten salt in the pilot scale tests were >5-9's and >6-9's. The DRE's ranged from >6-9's to >8-9's.
4) The chlordane DE achieved by the salt bed in the pilot-scale tests ranged >4-9's to 6-9's. The lower level of the range appeared to be due to an interference effect in the analysis of the melt. The DRE ranged from >5-9's to >7-9's.
5) The DRE for the total MSD pilot-scale system, which includes a baghouse, ranged from 9-9's to >10-9's for HCB and ranged from >7-9's to >8-9's for chlordane.
6) The bench-scale and pilot-scale tests with HCB resulted in >6-9's destruction efficiency in the operating temperature range of 900-1000°C. However, at a bench-scale test temperature of 803°C, the destruction efficiency decreased to 99.87%.
7) The tests discussed above were conducted with excess air. Tests were also made with deficient air (70-80% of

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*6-9's denotes 99.9999%
**5-9's 86 denotes 99.99986

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stoichiometric air) to determine the MSD performance at off-spec conditions. One such bench-scale test with HCB still resulted in >6-9's DRE. A similar bench-scale test with chlordane resulted in >4-9's DRE. A deficient air-chlordane test at the pilot-scale resulted in >7-9's DRE.

8) The concentration of $HC\ell$ in the off-gas of both the bench- and pilot-scale tests was <100 ppmv.

9) The DREs achieved in the bench- and pilot-scale units for both waste materials under corresponding test conditions were in good agreement.

CONCLUSIONS

The results of the Rockwell Molten Salt Destruction bench-scale and pilot-scale tests lead to the following conclusions:

1) A molten salt bed, operating at a temperature of 900-1000^{o}C, is highly effective in producing an off-gas free of hazardous waste input, and in meeting the TSCA requirements for PCB type materials.

2) Very high destruction and removal efficiencies for aromatic chlorinated materials are achievable by the overall Molten Salt Destruction system, which includes a baghouse in addition to the molten salt bed.

3) The MSD system can be safely operated at off-specification conditions of deficient air, which would not normally occur for an extended period.

4) Acid gases are efficiently absorbed by the molten salt bed, thereby eliminating the need for off-gas effluent scrubbing.

5) Molten salt destruction bench-scale test results are good predictors of pilot-scale performance of the MSD process.

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SECTION 3
RECOMMENDATIONS

The pilot-scale tests performed under this program utilized a general-purpose refractory-lined molten salt vessel which is not representative of the projected bare metal wall MSD hardware. Therefore, MSD system design data related to the commercial plant, such as maximum waste throughput rates, heat and mass balances, operating labor requirements, and control system operational reliability, could not be obtained with the pilot facility utilized in this program. This information, which is important to validating the commercial readiness of MSD, should be obtained through a test program conducted with a prototypical MSD process module. This transportable hardware is expected to be available in 1983. The following recommendations are offered:

1) Repeat the current pilot-scale program in the prototypical transportable unit, upon its availability to provide meaningful mass and thermal data.
2) Conduct longer duration tests to verify process stability and to provide sampling and analysis opportunities for long-term steady-state conditions.
3) Conduct more detailed analyses in order to provide quantitative measurements of the products of incomplete combustion (PICS) including dioxin and furans that may be generated in the destruction of the HCB and the chlordane.
4) Expand the pretest scope of work to develop and prove the requisite analytical procedure to assure the high sensitivity for measuring trace quantities of organic materials in sodium carbonate-sodium chloride mixtures. Minor difficulties were encountered in the chemical analysis of chlordane in the spent melt due to interferences produced by contaminants in the melt.

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SECTION 4

TEST APPARATUS

This report section describes the test apparatus used for (1) the bench-scale tests of hexachlorobenzene and chlordane and (2) the pilot-scale tests with the same waste materials.

BENCH-SCALE TEST APPARATUS

The major elements of the bench-scale Molten Salt Destruction (MSD) system are the molten salt destructor vessel, the solid-feed assembly, and the liquid-feed assembly. Schematics of the bench-scale MSD system for feeding solids and for feeding liquids are shown in Figures 2 and 3, respectively.

Molten Salt Destructor

The bench-scale molten salt destructor, which was placed in a walk-in hood, consisted of a 15.2-cm-ID x 91.4-cm-high (6 in. ID x 36 in. high) metal vessel mounted in a Type 321 stainless steel container. This stainless steel container, in turn, was contained in a 20.3-cm (8 in.) ID, four-heating zone clamshell Ohio Thermal electric furnace. There were three heating zones of 20.3 cm (8 in.) height and one of 30.5 cm (12 in.) height. The temperature of each zone was controlled by a silicon controlled rectifier (SCR) controller.

The temperature of the melt was determined by a chromel-alumel Inconel-sheathed thermocouple placed inside a metal thermowell immersed in the melt pool. Between experimental tests, the molten salt was maintained at the desired temperature with the electric furnace. When waste destruction was initiated, the heat input from the furnace was decreased since heat was then generated by oxidation of the organic material. In most cases, more than enough heat was generated than required to maintain the salt at the desired

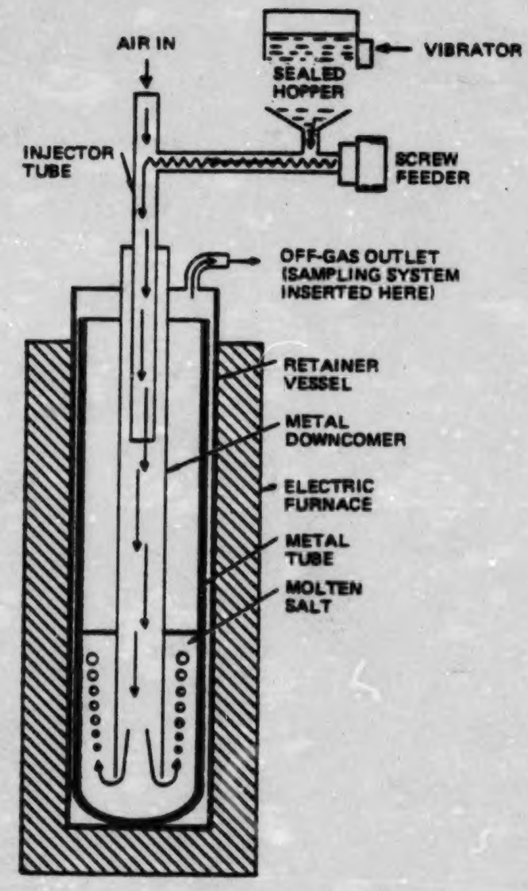
AIR IN
VIBRATOR
SEALED HOPPER
INJECTOR TUBE
SCREW FEEDER
OFF-GAS OUTLET (SAMPLING SYSTEM INSERTED HERE)
RETAINER VESSEL
METAL DOWNCOMER
ELECTRIC FURNACE
METAL TUBE
MOLTEN SALT

Figure 2. Bench-scale molten salt destructor
- with solids feed

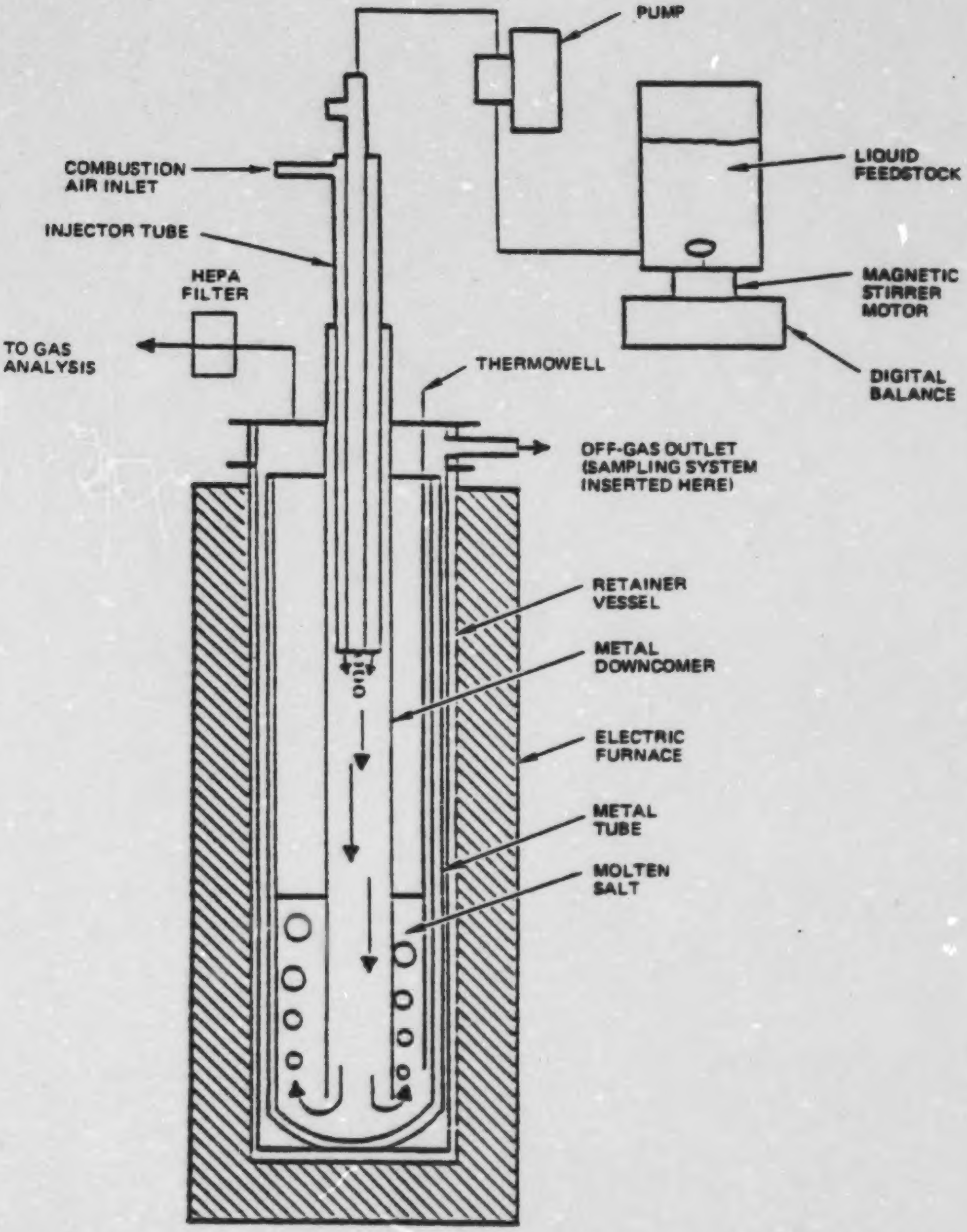
PUMP
LIQUID FEEDSTOCK
COMBUSTION AIR INLET
INJECTOR TUBE
HEPA FILTER
TO GAS ANALYSIS
MAGNETIC STIRRER MOTOR
DIGITAL BALANCE
THERMOWELL
OFF-GAS OUTLET (SAMPLING SYSTEM INSERTED HERE)
RETAINER VESSEL
METAL DOWNCOMER
ELECTRIC FURNACE
METAL TUBE
MOLTEN SALT

Figure 3. Bench-scale molten salt destructor with liquid feed

test temperatures. In such cases, in order to prevent the melt temperature from rising, an air-cooling system (not shown in Figures 2 or 3) was used to maintain a constant temperature. It consisted of an eight-hole air distribution ring mounted underneath the stainless steel retainer vessel. Air, at rates up to 500 l/min, could be passed upward between the outer surface of the retainer vessel and the furnace wall.

The 3.7-cm (1.5 in.) ID metal downcomer was adjusted so that its tip was ~1 cm above the bottom of the 15-cm (6 in.) diam. metal reactor tube. Thus, the waste-air mixture was forced to pass downward through the downcomer, outward at its bottom end, and then upward through about 15 cm of salt in the annulus between the 3.7-cm and the 15-cm metal tubes.

Solid-Feed Assembly

The HCB-coke mixture*# was metered from the hopper into the 1.2-cm-OD central tube of the injector by a screw feeder. The screw feeder was rotated by a 0-400 rpm Eberbach Corporation Con-Torque stirrer motor. The HCB was mixed with about 75% of the air being used for destruction, and this solid-air mixture was passed downward through the insulated center tube of the injector. The other 25% of the combustion air passed through a cooling annulus of the injector (shown in Figure 2). At the tip of the injector, the entire solid-air stream combined with the cooling air stream and the mixture emerged into the downcomer and then into the melt.

Liquid-Feed Assembly

The chlordane waste* was contained in a 4-liter stainless steel beaker. Feeding of the waste was accomplished with a Masterflex 7014 peristaltic pump. The waste flowed from the stainless steel beaker through 1.7-mm-ID (0.066 in.) Viton tubing to a 6.4-mm (1/4 in.) stainless steel line. This manifold contained a 0-0.103-MPa (0-15 psig) pressure gauge and a pressure switch set at

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*See Page 44 for more information on the wastes.

#Coke was used because it is an inexpensive low-ash fuel. A solid mixture was easier to feed than a solid-liquid mixture.

0.03 MPa (5 psig). The pressure switch was present to turn off the pump in the event of a blockage in the lines. The beaker containing the waste was located on a digital balance capable of reading 10-kg by 1-g increments. The use of flexible tubing between the pump and the feed beaker allowed for a continuous mass feed rate to be calculated from the balance display.

The waste passed through the stainless steel line and into a liquid injector. The liquid injector consisted of two concentric stainless steel annuli. The liquid passed down the center 0.71-mm (0.18 in.) ID tube, and the combustion air was added through the outside annulus. The outside of the injector was wrapped with ceramic insulation.

The injector was mounted inside a 4.2-cm (1-2/3 in.) ID metal downcomer. This downcomer extended to within 1.3 cm of the bottom of the 15.2-cm-ID Inconel tube. The flow rate of the air was continuously determined with a rotameter.

PILOT-SCALE TEST FACILITY

Background

The Rockwell International Molten Salt Test Facility (MSTF) was utilized for the pilot-scale tests. This facility was designed and built in 1974 as a general purpose molten salt test facility for the development of coal gasification, resource recovery, and radioactive waste volume reduction applications of the molten salt technology. Salt addition and withdrawal are continuous in the MSTF facility in contrast to the bench-scale system in which salt is added and removed batchwise. Thus, the MSTF maintains constant melt bed properties. As a general purpose facility, the MSTF contains design features which are different from the current commercial concept of the Molten Salt Destruction System for hazardous waste destruction. In addition to having equipment items that are present to provide operational versatility, the destructor vessel itself is uniquely different in that it is lined with alumina refractory whereas the commercial MSD system design for destruction of chlorinated organic wastes is based upon a metal alloy destructor vessel (identical to the

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material used for the bench-scale tests). These differences do not represent any substantive differences to process performance and do not compromise the applicability of this program's test results to commercial MSD systems.

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Description of MSTF

The molten salt destruction vessel at the MSTF is a vertical steel tank approximately 6.7 m (22 ft) high with a 1.2-m (4-ft) outside diameter. It is internally lined with a 0.15-m (6-in.)-thick refractory liner made from high-purity, fused cast alumina blocks. Four injection nozzles are provided on the combustor, located 90° apart from each other. Two of the opposing nozzles are angled 30° downward and are used for injection of preheated combustion air only. The other two opposing nozzles are horizontal and may be used for solids/fuel/waste/salt injection. One of these two nozzles also serves as a drain through which salt is tapped to empty the unit at system shutdown. Melt withdrawal is accomplished in a continuous overflow system; the overflow system consists of the melt withdrawal port located on the side of the vessel and has a 1.30-m (51-in.)-long 0.13-m (5-in.) ID horizontal refractory side arm, a 0.33-m (13-in.)-long, 3.8-cm (1.5-in.) ID vertical spout, and a spout burner assembly. A burner mounting block permits direct viewing into the destructor through the 0.13-m (5-in.) horizontal port. A cross sectional sketch of the MSTF vessel is shown in Figure 4.

The balance of the MSTF equipment consists of auxiliaries for materials storage and feed, off-gas processing and cleaning equipment, and supporting analytical and control instrumentation. A schematic of the plant equipment is shown in Figure 5. Two weigh belts are provided for metering the flow rates of salt and solid fuels; typically, coke or coal. A volumetric screw auger is used to feed nonhazardous solid wastes. Feed preparation for pneumatic conveying is done using a solids shredder and a hammermill. Off-gases from the combustor are routed through a short refractory-lined discharge line, the drop-out box, to either the secondary combustor and venturi scrubber or to the baghouse and then the venturi scrubber prior to being discharged to the atmosphere via the induced draft fan.

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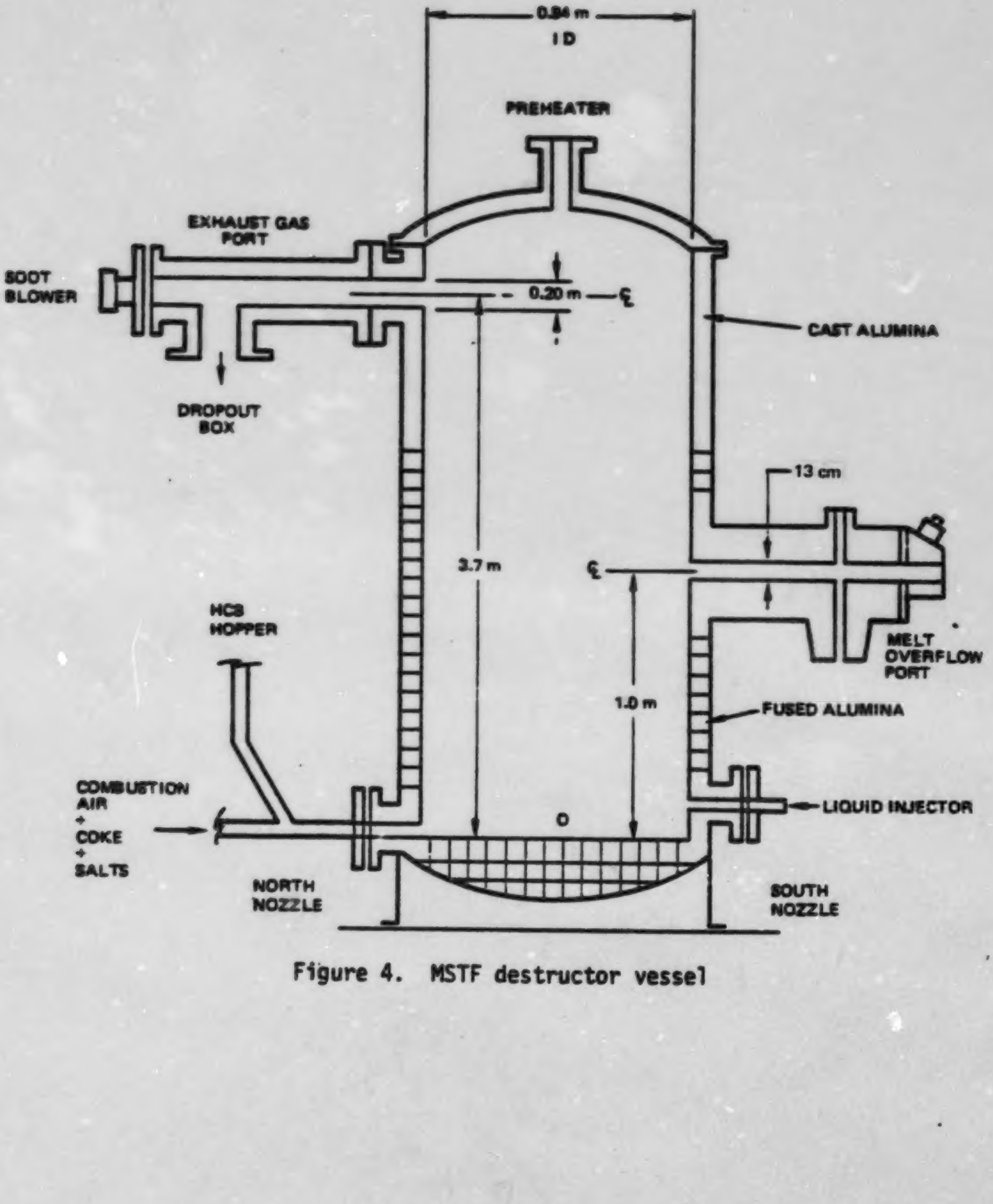
0.84 m
I D
PREHEATER
EXHAUST GAS PORT
SOOT BLOWER
0.20 m
℄
CAST ALUMINA
DROPOUT BOX
13 cm
3.7 m
℄
HCB HOPPER
MELT OVERFLOW PORT
1.0 m
FUSED ALUMINA
COMBUSTION AIR + COKE + SALTS
D
LIQUID INJECTOR
NORTH NOZZLE
SOUTH NOZZLE

Figure 4. MSTF destructor vessel

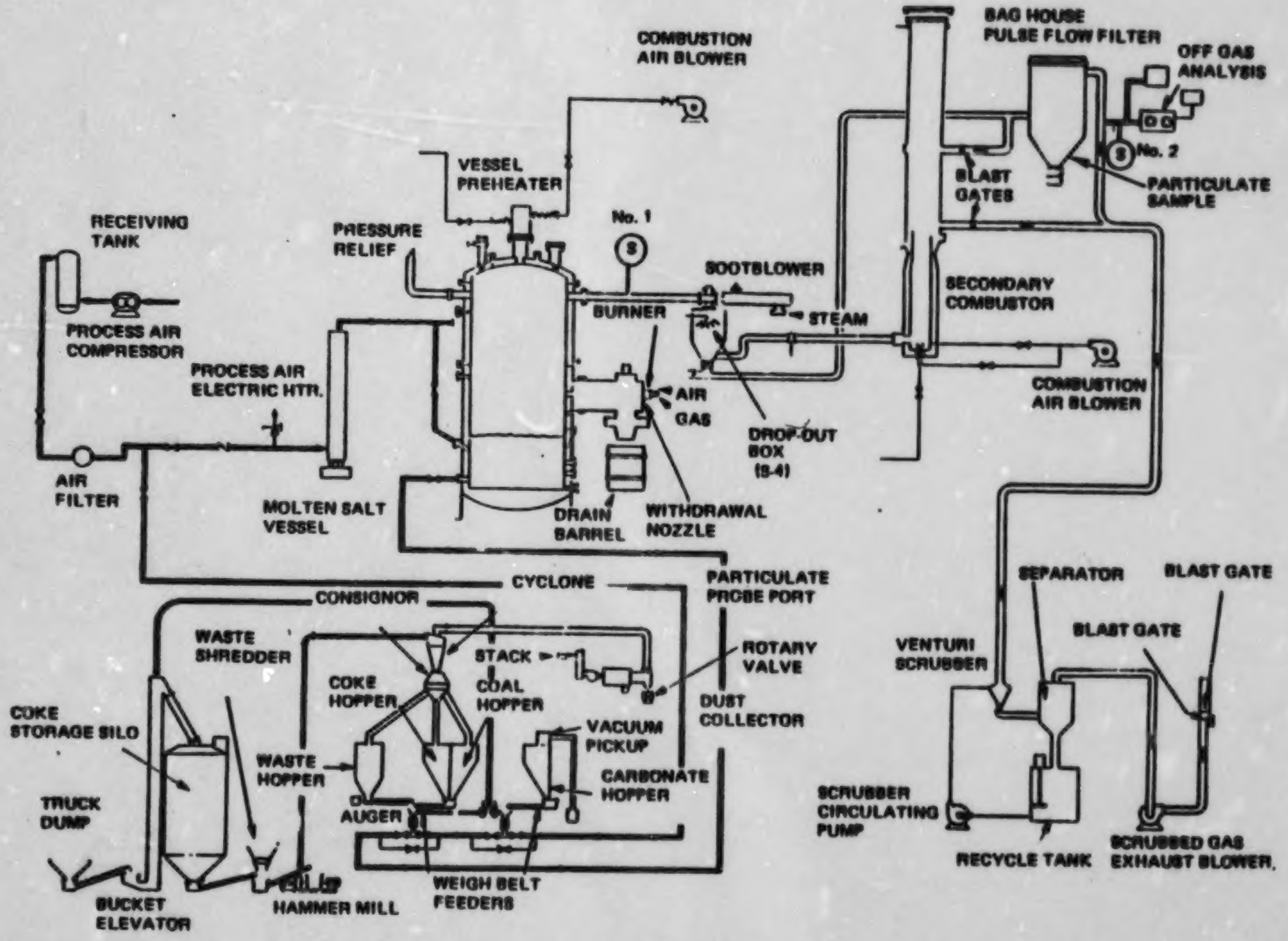
COMBUSTION AIR BLOWER
VESSEL PREHEATER
RECEIVING TANK
PRESSURE RELIEF
No. 1
S
SOOTBLOWER
PROCESS AIR COMPRESSOR
BURNER
STEAM
PROCESS AIR ELECTRIC HTR.
AIR
GAS
DROP-OUT BOX (S-4)
AIR FILTER
MOLTEN SALT VESSEL
DRAIN BARREL
WITHDRAWAL NOZZLE
BAG HOUSE PULSE FLOW FILTER
OFF GAS ANALYSIS
No. 2
S
BLAST GATES
PARTICULATE SAMPLE
SECONDARY COMBUSTOR
COMBUSTION AIR BLOWER
CYCLONE
PARTICULATE PROBE PORT
CONSIGNOR
WASTE SHREDDER
STACK
ROTARY VALVE
COKE HOPPER
COAL HOPPER
DUST COLLECTOR
COKE STORAGE SILO
VACUUM PICKUP
WASTE HOPPER
CARBONATE HOPPER
TRUCK DUMP
AUGER
BUCKET ELEVATOR
HAMMER MILL
WEIGH BELT FEEDERS
SEPARATOR
BLAST GATE
BLAST GATE
VENTURI SCRUBBER
SCRUBBER CIRCULATING PUMP
RECYCLE TANK
SCRUBBED GAS EXHAUST BLOWER.

Figure 5. Schematic of Molten Salt Test Facility

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The MSTF system as shown in Figure 5 is an open system at the salt withdrawal, spent salt interface. This facilitates the maintenance of continuous free-flowing molten salt in the melt withdrawal piping of the MSTF. For commercial applications, however, several salt withdrawal configurations are being considered. The design criteria include reliable performance and personnel and public safety.

PILOT-SCALE TEST SETUP

The test setup utilized for the pilot-scale experimental tests comprised several subsystems of the MSTF; the combustor, the spray cooler, the baghouse, and the induced draft fan. Figure 6 shows the major process items used in these tests with shading and heavy black lines. The spray cooler was inactive during the test and served only as passive equipment through which the exhaust gases passed. Cooling of the combustion gases as they passed through the pipe run to the baghouse was adequate for these tests without the addition of dilution air. Solid sodium carbonate-sodium chloride salt mixtures were fed continuously to the destructor using the salt weigh belt feed system. Coke was used as an auxiliary fuel and was fed using the coke weigh belt system.

Two additional feed systems were installed and checked out in support of the tests: (1) a hopper and rotary valve feeder for HCB solids, and (2) a feed tank, control valve, and liquid atomizer injector for chlordane. A schematic of the HCB feed system is shown in Figure 7. The HCB was metered out of the 1m x 1.3 m high lock hopper using a variable speed rotary valve and weigh cells under the hopper. The volume of the hopper was large enough that it required filling only once during the test. A variable-speed motor was used to change the rotational speed of the rotary valve for metering purposes. The valve had a displacement of 3.59×10^{-4} m^3/rev (0.0127 ft^3/rev) and a motor speed range of 1-30 rpm. The material was added to the injection port on the destructor just upstream of the coke and carbonate conveying line. Precautions were taken to insure minimal release of HCB material to the test area for health and safety reasons and to preclude contamination of sampling equipment. A handling procedure for HCB and chlordane was prepared for the

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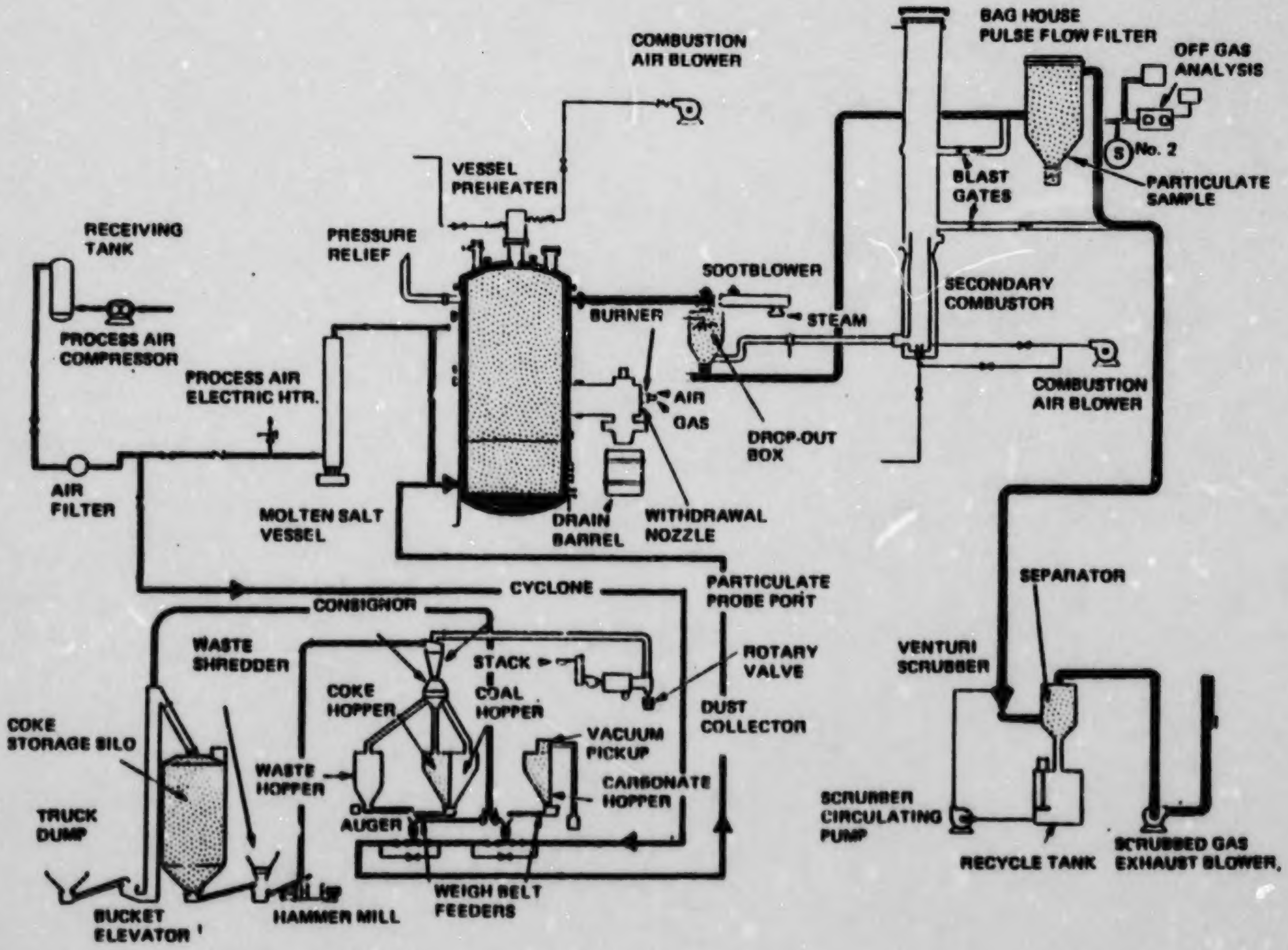
COMBUSTION AIR BLOWER
BAG HOUSE PULSE FLOW FILTER
OFF GAS ANALYSIS
No. 2
S
PARTICULATE SAMPLE
BLAST GATES
VESSEL PREHEATER
RECEIVING TANK
PRESSURE RELIEF
SOOTBLOWER
STEAM
SECONDARY COMBUSTOR
BURNER
PROCESS AIR COMPRESSOR
PROCESS AIR ELECTRIC HTR.
AIR
GAS
COMBUSTION AIR BLOWER
DROP-OUT BOX
AIR FILTER
MOLTEN SALT VESSEL
DRAIN BARREL
WITHDRAWAL NOZZLE
CYCLONE
PARTICULATE PROBE PORT
SEPARATOR
CONSIGNOR
WASTE SHREDDER
STACK
ROTARY VALVE
VENTURI SCRUBBER
COKE HOPPER
COAL HOPPER
DUST COLLECTOR
COKE STORAGE SILO
VACUUM PICKUP
WASTE HOPPER
CARBONATE HOPPER
SCRUBBER CIRCULATING PUMP
TRUCK DUMP
AUGER
BUCKET ELEVATOR
HAMMER MILL
WEIGH BELT FEEDERS
RECYCLE TANK
SCRUBBED GAS EXHAUST BLOWER,

Figure 6. Pilot-scale system schematic

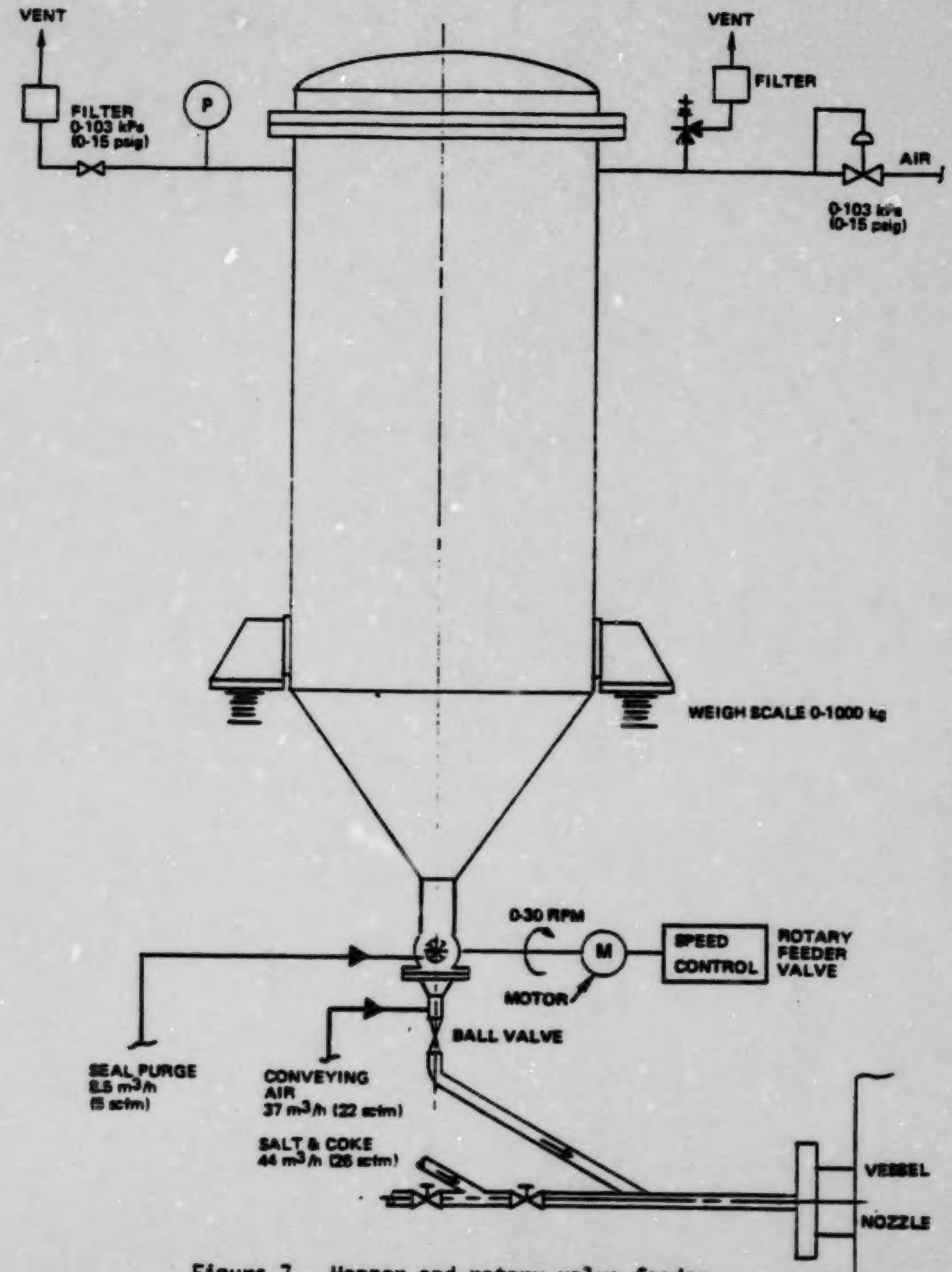
VENT
FILTER
0-103 kPa
(0-15 psig)
P
VENT
FILTER
AIR
0-103 kPa
(0-15 psig)
WEIGH SCALE 0-1000 kg
0-30 RPM
M
SPEED
CONTROL
ROTARY
FEEDER
VALVE
MOTOR
BALL VALVE
SEAL PURGE
8.5 m3/h
(5 scfm)
CONVEYING
AIR
37 m3/h (22 scfm)
SALT & COKE
44 m3/h (26 scfm)
VESSEL
NOZZLE

Figure 7. Hopper and rotary valve feeder

safety review and subsequently approved for test use. This procedure is presented in Appendix A.

Chlordane was fed from a 0.25-m^3 (65-gal) pressurized tank, filtered, and then passed into the atomizer gun through a flow control valve. The atomizer gun was a North American Co. Model 5622-02A of the kind normally used to fire boilers or process heaters. Oil was introduced at low pressure down the center of the gun and atomizing high-pressure air was introduced through an annular space around the oil at the nozzle tip. The high velocity of the air sheared the oil into fine droplets suitable for rapid combustion. Atomization air was provided at 345 kPa (50 psig) at the rate of 26 sm^3/h (15 scfm). Sweep air was provided around the oil gun at 68 sm^3/h (40 scfm) to cool the gun and to keep the gun port free of melt intrusion. Auxiliary fuel in the form of No. 1 or No. 2 diesel fuel was fed to the atomizer whenever chlordane was not fed. A schematic illustrating the liquid injection system is shown in Figure 8.

Process Data Acquisition

Process data were recorded primarily on the MSTF computerized data acquisition system. This data system was located on the operator console in the MSTF Control Room. Recording equipment and gas analysis process equipment were also located in the Control Room.

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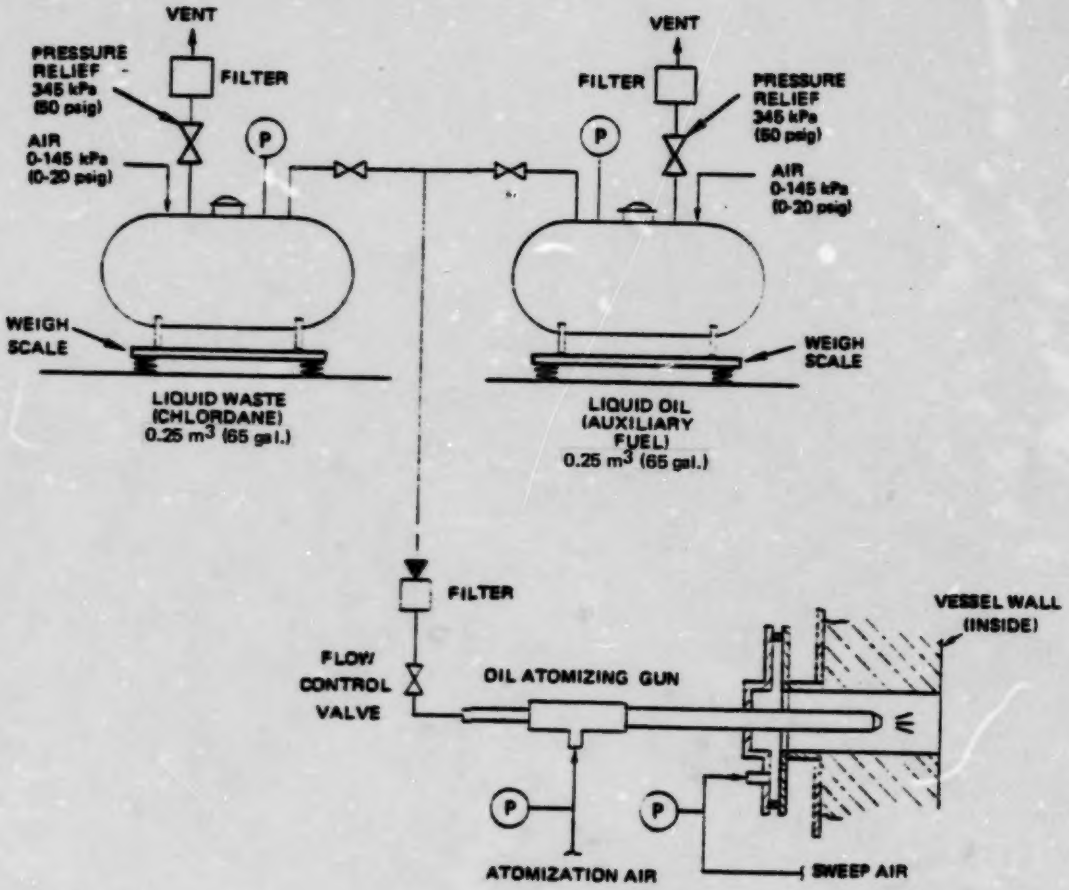
VENT
PRESSURE RELIEF 345 kPa (50 psig)
FILTER
AIR 0-145 kPa (0-20 psig)
P
WEIGH SCALE
LIQUID WASTE (CHLORDANE) 0.25 m3 (65 gal.)
VENT
FILTER
PRESSURE RELIEF 345 kPa (50 psig)
P
AIR 0-145 kPa (0-20 psig)
WEIGH SCALE
LIQUID OIL (AUXILIARY FUEL) 0.25 m3 (65 gal.)
FILTER
FLOW/ CONTROL VALVE
OIL ATOMIZING GUN
VESSEL WALL (INSIDE)
P
P
ATOMIZATION AIR
SWEEP AIR

Figure 8. Liquid injection system

SECTION 5

MATERIALS AND ANALYTICAL METHODS

DESCRIPTION OF WASTES

Two separate waste materials were tested in both the bench-scale and pilot-scale tests. These waste materials were: (1) solid hexachlorobenzene and (2) liquid chlordane.

Technical-grade powder hexachlorobenzene was purchased from Hummel Chemical Company, South Plainfield, New Jersey. It contained 98 wt % HCB and 2% inerts. The elemental composition of pure HCB, in weight %, is given in Table 2.

The chlordane was purchased from Ronco Chemical, Inc., Anaheim, California. The material as received contained 73.11 wt % technical chlordane, 19.89 wt % kerosene, and 7.00 wt % inerts. The technical chlordane portion consisted of 60% octachloro-4,7-methanotetrahydroindane ($C_{10}H_6Cl_8$) and 40% related compounds. The chlordane, as received was analyzed onsite. The elemental composition of this mixture, as received, is also shown in Table 2:

TABLE 2

ELEMENTAL COMPOSITION OF HCB AND CHLORDANE

Element	Composition (wt %)	
	Pure HCB	Chlordane (as received)
C	25.3	44.7
Cl	74.7	46.4
H	0.0	4.97
Inert		4.1

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ANALYTICAL CHEMISTRY METHODOLOGY

This report section describes the methodology utilized to evaluate the destruction efficiency and general performance of the molten salt process in bench-scale and pilot-scale tests of HCB and chlordane waste destruction.

Although the described methodology was generally applied to both the bench-scale and pilot-scale tests, slight modifications were made in the latter tests as a result of experience gained in the bench-scale test which preceded.

Analysis of Combustion Products in Off-Gas

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On-Line Analyses--

The on-line combustion off-gas analysis flow chart is shown in Figure 9. A portion of the off-gas was first passed through a HEPA filter to remove particulates. The filtered gas was analyzed for NO_x, CO, CO_2, O_2, N_2, and unburned hydrocarbons. A water-ice trap was used to remove most of the water vapor upstream of all the analyzers except the NO_x and hydrocarbon analyzers. An ice trap was not used in the NO_x line because some NO_2 might be condensed with the water. The NO_x analyses were made with a Thermo Electron Corporation Model 10A chemiluminescent NO_x analyzer. The CO_2 and CO were continuously monitored using Model PIR-2000 Olson-Horiba nondispersive-infrared meters. The hydrocarbon content of the gas was continuously monitored using a Beckman Model 402 hydrocarbon analyzer. This analyzer used a flame ionization detector. The unit was calibrated using calibration standards containing propane in air (324 and 828 ppm), but for simplicity, the calibration was set to read out the hydrocarbon content of the gas expressed as CH_4. The oxygen content of the gas was continuously monitored with a Teledyne portable oxygen analyzer, Model 320. For the bench-scale tests, a complete gas analysis was made every 10 min. using a Hewlett-Packard Model 5840 computerized gas chromatograph. Constituents determined with this chromatograph were CO_2 using a Poropak T column and CO, H_2, N_2, CH_4, and O_2 + Ar (oxygen and argon come through unseparated) using a molecular sieve 5A column. For the pilot-scale

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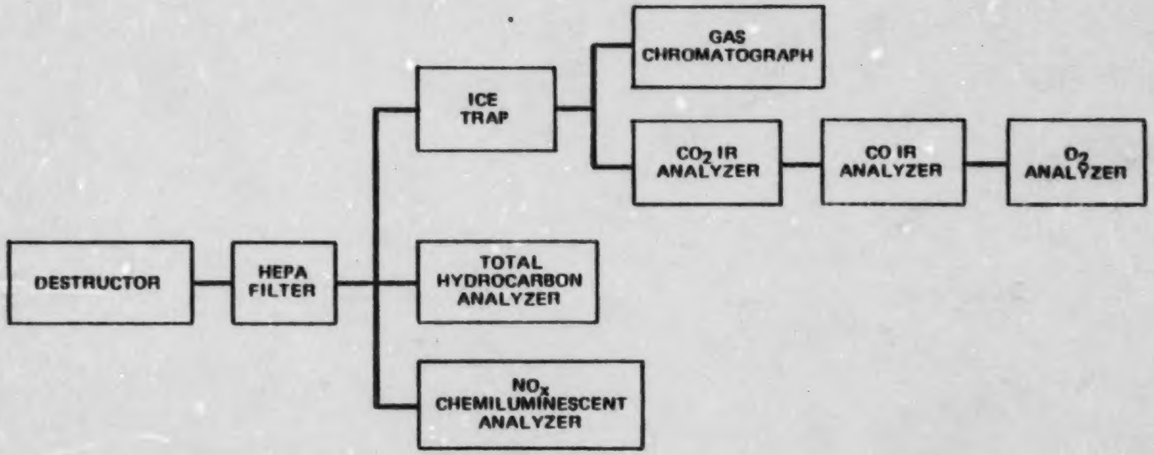
DESTRUCTOR
HEPA FILTER
ICE TRAP
GAS CHROMATOGRAPH
CO_2 IR ANALYZER
CO IR ANALYZER
O_2 ANALYZER
TOTAL HYDROCARBON ANALYZER
NO_x CHEMILUMINESCENT ANALYZER

Figure 9. On-line combustion off-gas analysis flow chart

tests, which were conducted at a remote Rockwell facility, the on-line off-gas analyses were made with a Honeywell H-1000 Process Gas Analyzer.

Particulate Loading--

The particulate loading was determined by taking particulate samples at the off-gas outlet using a Riley Environeering sampling nozzle. This device used a heated-glass fiber filter to remove particulates without the problem of moisture condensation. The filter was No. 25 Schleicher and Schuell glass fiber; it had a removal efficiency of 99.97% on dioctylphthalate droplets greater than 0.3 um. The particulates were collected on the fiberglass filter held in a sealed and heated (about 65°C) filter holder assembly. A sampling area of 140 cm^2 (21.7 $in.^2$) was used. The volume of gas passing through the filter was measured with a wet test meter. The particulate loading of the off-gas was determined from the weight gain of the filter and the total gas flow through the filter.

HCl, Cl_2, and Phosgene--

The off-gas from the bench-scale tests was sampled periodically for HCl, Cl_2, and phosgene, using Drager tubes. The Drager method involved drawing a known amount of gas through a glass tube containing a dry reagent. The quantity of gas, in ppm, was indicated by the length of reagent that was discolored during the test. The off-gas exiting the exhaust port was cooled by trapping it in an inverted gas cup. It was then sampled with the Drager tubes. After the test was completed, a blank was obtained by sparging air through the melt and sampling the exhaust air with a Drager tube. In the case of the pilot-scale tests, the off-gas was sampled during three test runs for HCℓ. Based on the findings of the bench-scale tests in which no chlorine or phosgene was detected, it was deemed unnecessary to analyze the off-gas for chlorine or phosgene.

Sampling to Determine Destruction of HCB and Chlordane Wastes

Two sets of samples were generally obtained in each test. In order to obtain a preliminary result soon after each test, samples were taken and analyzed onsite. Then samples were taken and submitted to the Environmental

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Monitoring & Services Center (EMSC) of Rockwell International at Newbury Park, California, for chemical analyses for this program.

The sampling techniques and procedures were developed, implemented with, and monitored by EMSC. The sampling procedure using polyurethane foam plugs to collect any HCB, chlordane, and degradation products was based on the work by the EPA (4,5) and by the U.S. Department of Agriculture. (6)

Bench-Scale Samples--

Samples Submitted to EMSC for Determination of HCB--An aliquot of about one twenty-fifth (4%) of the off-gas from the destructor was sampled at the off-gas port with the sampling apparatus shown in Figure 10. The function of each component of the sampling system was as follows:

1) Probe — inserted into the off-gas port to obtain a sample of the hot off-gas.
2) Deflector — to deflect the off-gas stream that was not sampled away from the rest of the sampling apparatus.
3) Heated Glass Fiber Filter — to remove particulates from the gas stream thus preventing plugging of the polyurethane foam plug or impingers. The temperature of the filter was maintained at 80°C to prevent condensation of water on the filter.
4) Heat Exchanger — to cool the gas to prevent melting of the polyurethane foam plug; it provided the proper adsorption temperature.
5) Polyurethane Foam Plug — to capture HCB in the off-gas.
6) Impingers — The two impingers contained ~70 ml of toluene and trapped any HCB or other organic chlorine compounds which escaped the polyurethane foam plug.
7) Ice Bath — to cool the impinger solutions to minimize vaporization of solvents.
8) Pump — to draw the sample through the sampling system.
9) Wet Test Meter — to measure the volume of gas sampled.

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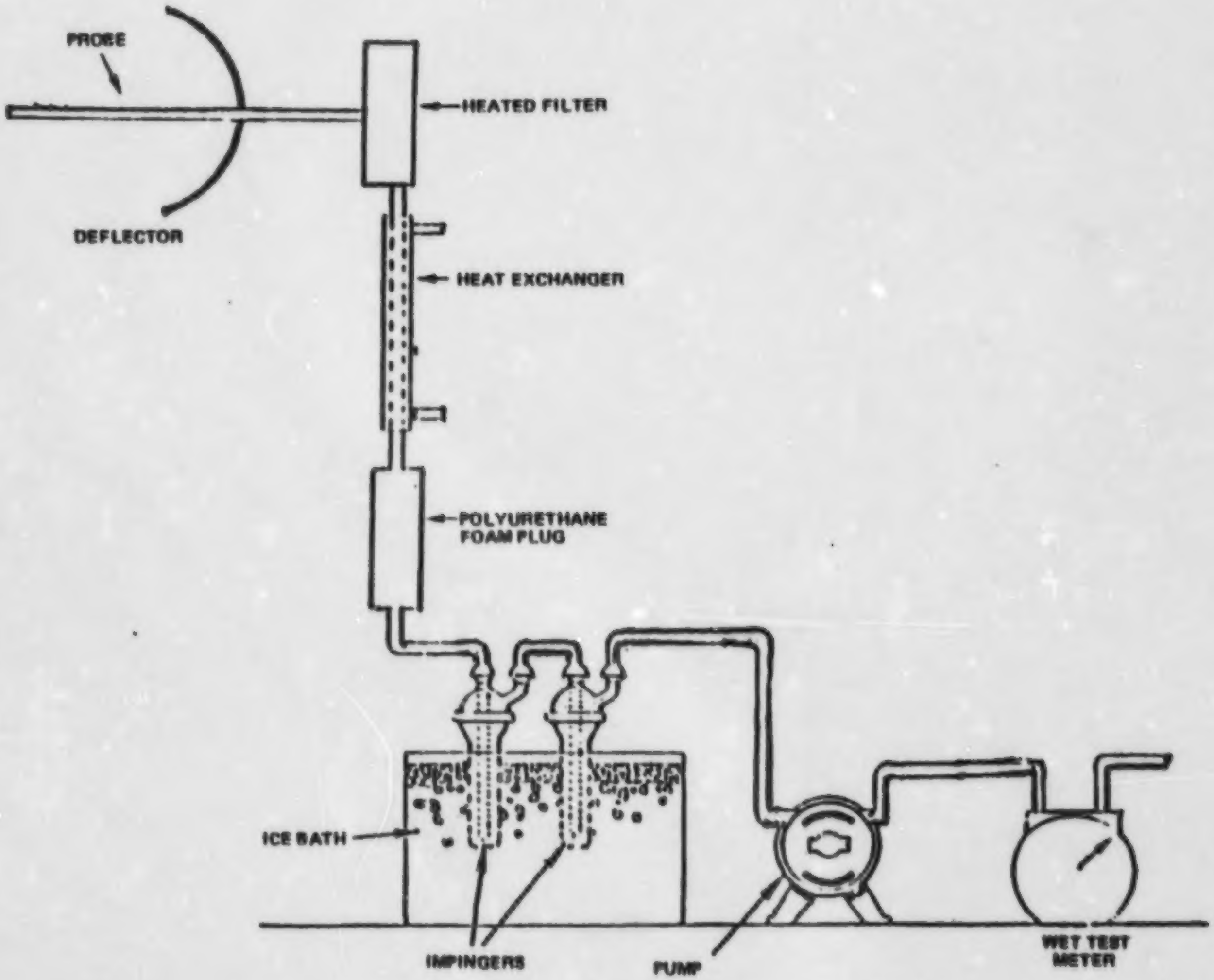
PROBE
DEFLECTOR
HEATED FILTER
HEAT EXCHANGER
POLYURETHANE FOAM PLUG
ICE BATH
IMPINGERS
PUMP
WET TEST METER

Figure 10. HCB sampling system for off-site analysis

After each sampling period, the glass fiber filter and the polyurethane foam plug were carefully removed and placed in their respective containers. The interior of the probe, filter holder, and heat exchanger were washed with benzene into a glass bottle. The Teflon tubing connecting the polyurethane plug to the impingers was washed along with the impinger solutions into another glass bottle.

After each burn period, the salt bath was sampled. Sampling was done by dipping a cold 1.2-cm (1/2 in.) diameter stainless steel rod into the turbulent salt bath and quickly removing the rod. Under those circumstances, a layer of salt froze on the rod. The salt could then be recovered by chipping it off with a hammer. After the waste feed was stopped, air was sparged through the melt for 15-45 min and another melt sample was taken.

Thus, for each HCB bench-scale test, the following samples were submitted to EMSC for analysis:

1) Glass fiber filter
2) Polyurethane plug
3) Combined impinger solution
4) Combined probe, filter housing, and heat exchanger washing
5) Melt samples.

Modifications of the sampling system were made for the remaining bench-scale and for the pilot-scale tests. A summary of the components of the sampling system for the various tests is shown in Table 3, where the modifications can be readily seen.

Samples Analyzed Onsite for Determination of HCB--The onsite analysis was performed on off-gas samples only. The particulate filter and polyurethane foam plug were eliminated, and an additional impinger solution was added. Thus, the impinger solutions also contained the particulates. The elimination of the particulate filter and foam plug permitted a quick analysis of the sampled off-gas without further treatment. The function of the components was essentially as described previously. After the off-gas sampling period, each

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individual impinger solution was analyzed by electron capture gas chromatography. The probe, filter housing, and heat exchanger interior were washed and analyzed by the same GC technique.

TABLE 3

MAJOR COMPONENTS OF OFF-GAS SAMPLING SYSTEM*

Waste	Size of Destructor	Where Analyzed	Heated Glass Fiber Filter	Heat Exchanger	Polyurethane Foam Plugs	Impingers
HCB	Bench	Off-site	Yes	Yes	1	2
		Onsite	No	Yes	0	3
Chlordane	Bench	Off-site	Yes	Yes	2	1
		Onsite	No	Yes	0	3
HCB	Pilot**	Off-site	Yes	Yes	1	0
		Onsite	No	Yes	0	2
Chlordane	Pilot**	Off-Site	Yes	Yes	1	0
		Onsite	No	Yes	0	2

*At Sampling Location 1, components also included the probe, deflector, ice bath, pump, and wet test meter

**At Sampling Location 2, the sampling train consisted of the filter, a foam plug, and one impinger.

Samples Submitted to EMSC for the Determination of Chlordane--The off-gas from the destructor was sampled for chlordane with the sampling apparatus which was similar to that for HCB, except for the changes as shown in Figure 11. The chlordane sampling system used a second polyurethane foam plug (PFP) in series as a backup to the first. In the case of chlordane, the efficiency of the PFP has been demonstrated to be greater than 98%.(6) Also, the sensitivity of the chlordane by electron capture gas chromatography was such that the use of only impinger solutions to back up the PFP would not have resulted in the required detection limit. The use of two plugs was sufficient for trapping the chlordane; however, one toluene impinger was used to trap possible degradation products which might not have been removed by the PFP.

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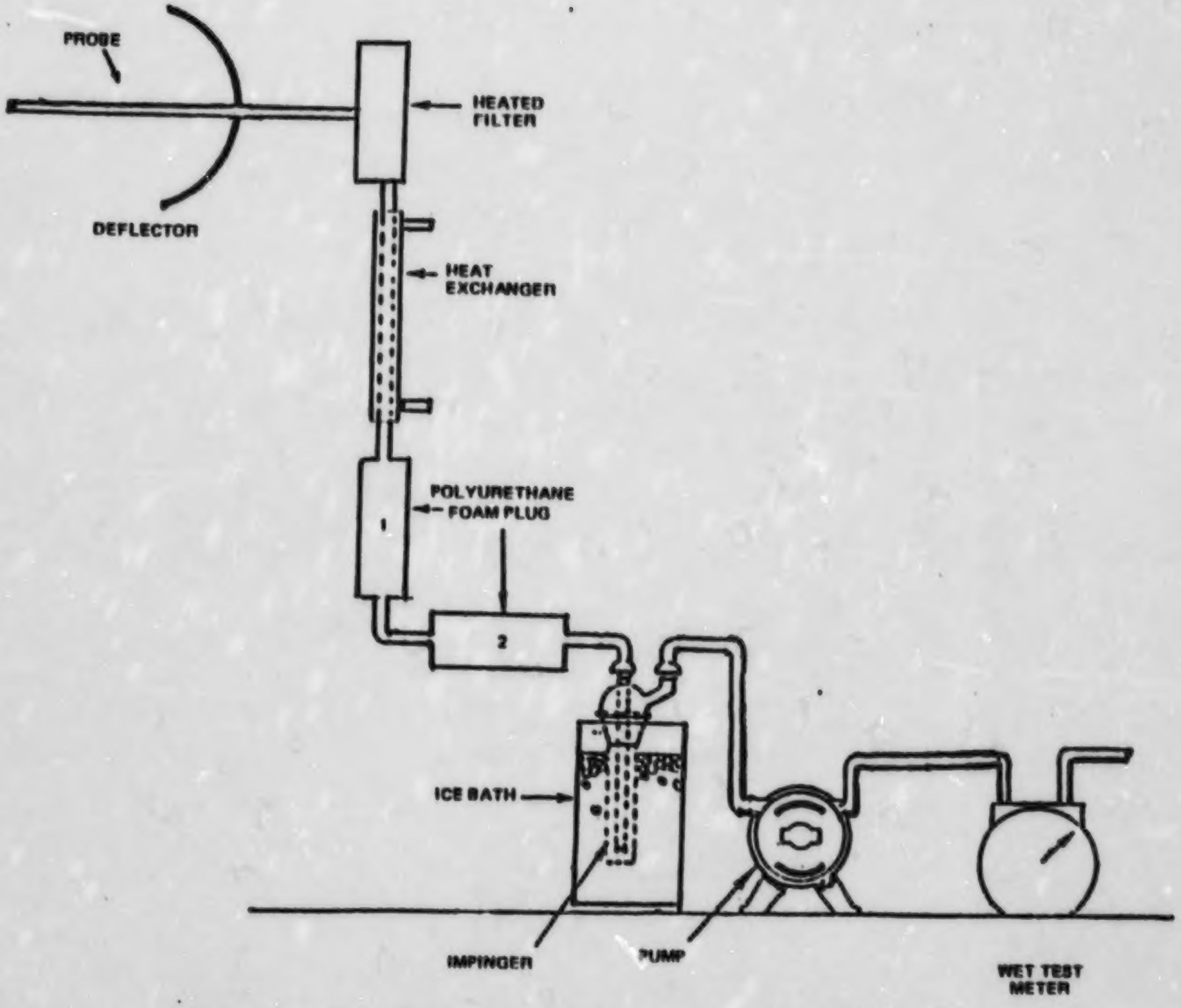
PROBE
DEFLECTOR
HEATED FILTER
HEAT EXCHANGER
POLYURETHANE FOAM PLUG
1
2
ICE BATH
IMPINGER
PUMP
WET TEST METER

Figure 11. Chlordane sampling system for off-site analysis

Thus, for each chlordane bench-scale test, the following samples were submitted to EMSC for analysis:

1) Glass fiber filter
2) Two polyurethane plugs
3) Impinger solution
4) Combined probe, filter housing, and heat exchanger washing
5) Melt samples.

Samples Analyzed Onsite for Chlordane--As in the case of HCB, the onsite analysis was performed on off-gas samples only. The sampling apparatus used was the same as that used for HCB onsite analysis.

Pilot-Scale Samples--

The components of the sampling system for the pilot-scale tests are shown in the lower half of Table 3. The off-gas from the molten salt vessel was sampled for HCB and chlordane in two locations: (1) just downstream of the destructor vessel and (2) just downstream of the baghouse. Figure 12 is a simplified schematic of the process showing these two locations. Two kinds of samples were taken at the first location. One type was taken with two impingers containing toluene, and the second was taken with only a polyurethane plug.* The first type of sample was used for analysis onsite to provide rapid operational information on the destructor performance, while the second sample type was taken to the Environmental Monitoring & Services Center for a detailed and more rigorous analysis. At the second location, samples were taken with a particulate filter, a polyurethane plug, and an impinger solution. Samples taken at Location 2 represent the quantities of HCB or chlordane that would be potentially released via the combustor exhaust stack and thus are the basis for calculating the overall process destruction and removal efficiency.

Melt samples from the overflow of the vessel salt bed were taken in a cup, and off-gas particulates were taken from the baghouse hopper.

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*The bench-scale experiments showed that one foam plug was sufficient to capture all the undestroyed HCB and chlordane.

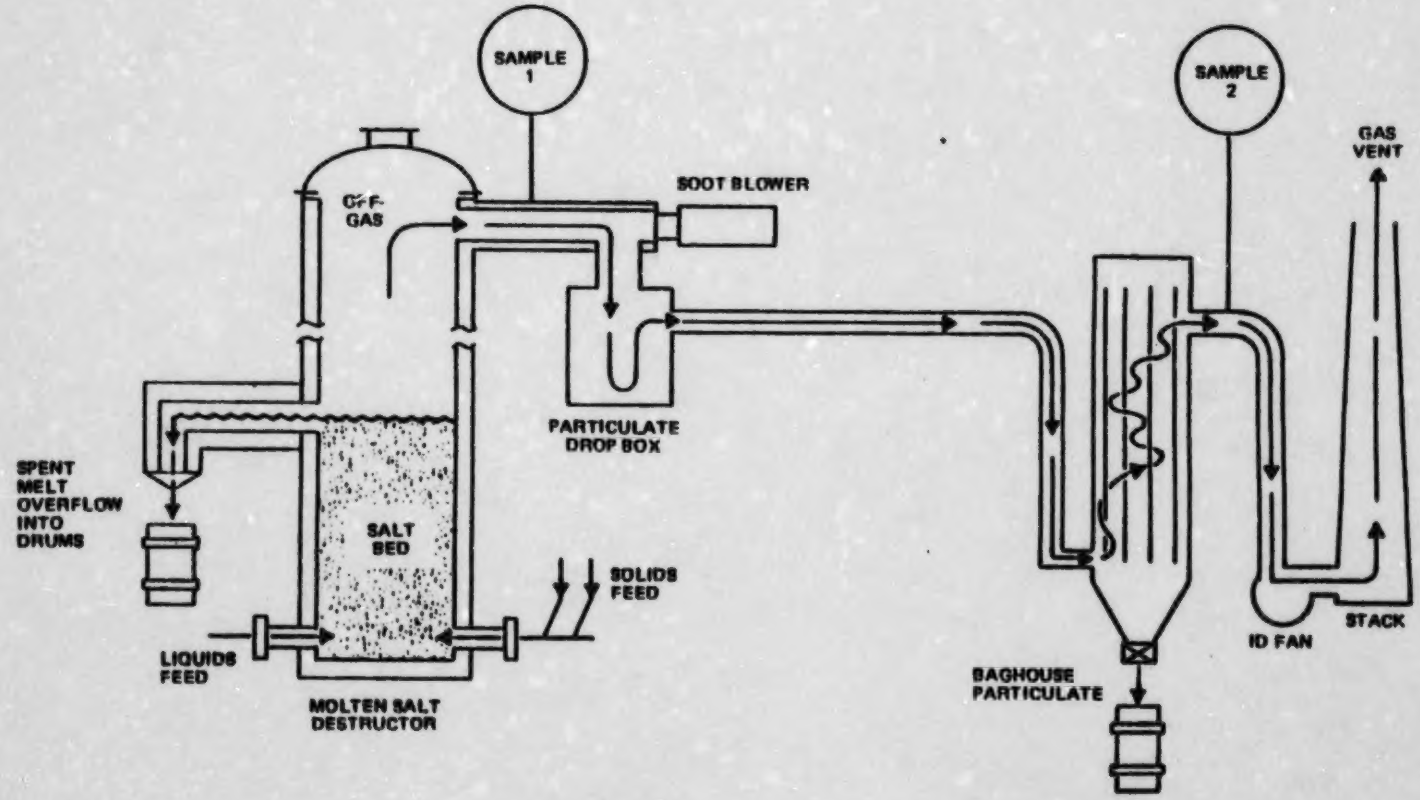
SAMPLE 1
SAMPLE 2
GAS VENT
SOOT BLOWER
OFF-GAS
PARTICULATE DROP BOX
SPENT MELT OVERFLOW INTO DRUMS
SALT BED
SOLIDS FEED
LIQUIDS FEED
MOLTEN SALT DESTRUCTOR
BAGHOUSE PARTICULATE
ID FAN
STACK

Figure 12. Off-gas sampling locations: pilot-scale system

For each test, off-gas filter, plug, melt, and probe wash samples downstream of the destructor were taken and a filter, plug, and impinger solution samples downstream of the baghouse were analyzed.

The laboratory analyses of the extracted HCB and chlordane was done in accordance with EPA Methods 612 and 608, respectively.(7)

Sample Extraction and Concentration

Bench-Scale Samples--

Glass Fiber Filters--These were placed in Soxhlet extractors and extracted with 110 ml methylene chloride for about 10 h. The extracts were each filtered through a 3 μm filter into a Kuderna-Danish evaporator fitted with a 5 ml receiving finger. The extracts were concentrated over a hot water bath to about 3 ml; 20-ml hexane was then added, and the combined extract was reconcentrated to 3-5 ml. The extracts were then transferred to vials with a Teflon-lined cap and stored at 4°C if immediate analysis was not possible.

Polyurethane Foam Plugs--Each foam plug was carefully placed on the bottom of a Soxhlet extractor, and about 25-ml methylene chloride was used to rinse the inside of the glass plug holder into the extractor. Each plug was then extracted and concentrated in the same manner as the fiberglass filter extracts previously described.

Melt Samples--The entire sample submitted for each melt was dissolved in 150-200 ml distilled water. The pH of the solution was adjusted to 7 using concentrated hydrochloric acid. The solution was then successively extracted in a 1-liter separatory funnel with three 60 ml aliquots of methylene chloride. The combined methylene chloride extracts were filtered through a 3 μm filter to remove any particulates and a column of anhydrous sodium sulfate to remove any water. The filtrate was collected in a Kuderna-Danish evaporator. The extract was concentrated in the same manner as the fiberglass filter extracts.

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Washing and Impinger Solutions--Most of these were analyzed as received with no further treatment.

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Pilot-Scale Samples--

Plugs, Filters, and Probe Washes--The off-gas plug and filter for the same run were extracted together using methylene chloride; the probe wash was added to the extract and this solution was concentrated to 1.0 ml in hexane. The sample was then cleaned in a 1/2-in. Florisil column with no dilution. The filter and plugs downstream of the baghouse were done in the same manner.

Impinger Solutions--The impinger solutions from Sample 1 location were analyzed as received with no further preparation.

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The impinger solutions taken from Sampling Location 2 (downstream of the baghouse) were each poured into a stoppered graduated cylinder, and hexane or distilled water was added as needed. All samples contained some aqueous phase and some organic phase. The two phases were shaken together for a minute and allowed to separate. The organic phase was dried with anhydrous sodium sulfate and analyzed for HCB or chlordane. The aqueous phase was washed through a 1-in. column of activated charcoal, and the pH was measured using a pH meter. (Attempts to measure the pH prior to the activated charcoal wash were unsuccessful, resulting in reproducibility errors of ±2.0 units or more.) The pH was measured to determine the HCl concentration of the off-gas downstream of the baghouse.

Melt Samples--Salt samples were weighed, dissolved in 200 ml distilled water, and frozen until extracted. Prior to extraction, the frozen mixture was thawed and the pH was adjusted to 6-8 using concentrated hydrochloric acid. Each melt was extracted with methylene chloride and concentrated to about 1 ml. Cleanup was performed using disposable Florisil columns and the total volume was brought to 5.0 ml.

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Gas Chromatographic Analyses--

Bench-Scale Analysis--Analyses of hexachlorobenzene and chlordane in the extracted samples were conducted using a chromatograph equipped with an electron capture detector. Separate conditions were used for HCB and chlordane analyses. The chromatographic column was a 183-cm x 2-mm-ID, 6.4-mm OD glass column packed with 100/120 Supelcoport coated with 1.5% SP2250 and 1.95% SP2401. This column was recommended in EPA Method 608 for organo-chlorine pesticides and PCB analyses. (7) The GC parameters are given in Table 4.

Samples were run in duplicate, and an injection of a QC standard was done on at least every tenth injection to monitor instrument stability. For HCB, a sample peak was positively identified if its retention time (~6 min) matched that of standard HCB. For chlordane, the analytical technique used was essentially that of pattern recognition. This technique is based on the fact that the gas chromatography of chlordane has a unique elution pattern. The four major peaks at retention times of approximately 2.6, 4.2, 6.3, and 8.0 minutes were used. Positive identification was assumed when all four peaks were observed.

TABLE 4
GC PARAMETERS

Instrument:	Varian Gas Chromatograph, Model 3700
Column:	183 cm x 2 mm ID, 6.4 mm OD packed with 1.5% SP 2250 + 1.95% SP 2401 on 100/120 mesh Supelcoport, at 150°C (HCB) or 185°C (chlordane)
Injector:	On column at 180°C (HCB) or 210°C (chlordane); new high-temperature septum was installed daily
Detector:	Electron capture (^{63}Ni) at 350°C, range 10^{-11} amp/mV
Carrier gas:	Prepurified N_2 at 30 psi (20 cc/min)

Standard calibration curves were established by injecting dilutions of known amounts of HCB and chlordane.

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In some cases when hexachlorobenzene or chlordane was detected by the GC-EC analyses, their identification was confirmed by a gas chromatograph-mass spectrometer (GC-MS) using characteristic ions at m/e 284 for HCB and m/e 373 for chlordane. Only the electron impact mode was used in GC-MS work. Analyses were performed using a 30 m x 0.25-mm ID fused silica column coated with SE-54. This column was used instead of the Supelcoport column because it was more sensitive and provided better resolution to determine the degradation products. Daily instrument calibration was performed use a 50 ng injection of decafluorotriphenylphosphine (DFTPP). Degradation products were also analyzed, and their mass spectra were searched and compared to EPA/NIH or special priority pollutant libraries to identify the most probable chemical compounds. The GC-MS parameters are given in Table 5.

Pilot-Scale Analyses--Analyses of HCB and chlordane were conducted using a Varian gas chromatograph, Model 3700, equipped with an electron capture detector, as in the bench-scale tests. The chromatograph was connected to a Varian 9176 linear recorder and an HP3390A integrator. The GC parameters were the same as those given in Table 4.

TABLE 5

GC-MS PARAMETERS

Instrument:	Finnigan Model 4021 GC/MS/DS
Column:	30 m x 0.25-mm ID fused silica column SE-54
Injection Temperature:	225^{o}C
Column Temperature:	30^{o}C to 250^{o}C at 10^{o}C/min
Sep. Line Temperature:	250^{o}C
Column Head Pressure:	15 psig
Splitters:	Initially at 30^{o}C for 1 min
Sweep:	At 20 cc/min
Split:	At 40 cc/min
Carrier Gas:	He
Mass Spectrometer:	1 sec/scan 70 ev 1200 em voltage Calibration comp. 50 ng DFTPP

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For HCB, a sample peak was positively identified if its retention time (~4.3 min using the solvent peak as zero) matched that of standard HCB.

In the case of chlordane, the multiple peak pattern of chlordane was divided into three groups of peaks:

Group 1 = peaks eluted before 3.2 min
Group 2 = peaks eluted between 3.2 min and 6.9 min
Group 3 = peaks eluted after 6.9 min.

Only the third group peaks were considered for calculation of the chlordane DE and DRE values. The shapes of the third group peaks were more characteristic of chlordane as compared to the peaks of the first and second groups. The products of incomplete combustion (PICS) would be expected to come out with the earlier groups. It was outside the scope of the current program to completely identify the various PICS.

The GC-MS analyses were conducted in the same manner as in the bench-scale tests.

ANALYTICAL QUALITY ASSURANCE AND CONTROL

The test program was covered by standard QA procedures established by the Environmental Monitoring and Services Center. This included periodic calibration of instrumentation used by EMSC, traceable to the National Bureau of Standards. The analyses of noted samples were performed and reported by EMSC, acting as an independent agent, using modified EPA Methods 612 and 608 to ensure that the data reported were based on accepted standards.

Linearity standards were run on the gas chromatograph at least once daily; quality control standards were run at least after every five samples. Spiking and standard addition were done as needed. The integrator printed the retention time and relative area for each "peak" it recognized. In cases where a critical peak was too small to be integrated, peak heights were measured on the linear recorder.

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A complete evaluation of the sampling equipment was made by the EMSC prior to each test run to ensure that the individual components in the sampling trains were free from HCB and chlordane contamination. Reagent blanks and a method blank were performed to insure that all glassware, polyurethane plugs, sampling lines, heat exchanger, and reagents were interference-free. An analytical laboratory in a building remote from the test facility was used as a further effort to minimize contamination. Access to the lab was strictly limited to the analytical personnel responsible for sample gathering.

All glassware and sampling bottles were checked for HCB and chlordane by extracting them with solvents. Hexane or toluene blanks were also frequently run on the solvents. Laboratory replicates were analyzed to validate the precision of analysis, and spiked samples were analyzed to estimate the percent recovery.

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SECTION 6

BENCH-SCALE TESTS

This report section describes the MSD bench-scale destruction tests of HCB and chlordane. Descriptions of the waste streams, test conditions, test results, and discussion are presented.

WASTE STREAMS

Since the objective of the bench-scale tests of HCB and chlordane destructions was to generate a data base for the MSD pilot-scale tests, the bench-scale tests were conducted to provide a simulation of the planned pilot-scale test conditions to the extent that this was feasible. In accord with this approach, the waste streams fed to the bench-scale unit included the addition of high heating value materials such as coke or kerosene to the as-received HCB and chlordane, respectively. See Section 7, Page 67, for further explanation. The waste stream compositions are described below.

HCB

The higher heating value (HHV) of HCB calculated from the elemental composition was only 8304 kJ/kg (3570 Btu/lb). In order to increase the heating value, sufficient coke which contained 89.5 wt % carbon, 3.7% hydrogen, and 0.8% oxygen was added to the HCB. The resultant HCB-coke mixture contained 69.6 wt % HCB and 30.4% coke. The elemental composition of the HCB-coke mixture is shown in Table 6 and corresponds to a higher heating value of 16,280 kJ/kg (7000 Btu/lb). The empirical formula for the HCB-coke mixture was $C_{3.74}H_{1.11}O_{0.02}Cl_{1.46}$.

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Chlordane

The higher heating value (HHV) of the chlordane was 18,190 kJ/kg (7820 Btu/lb). It was planned that the chlordane, as received, would be diluted with the further addition of kerosene for the pilot-plant tests. The composition of the diluted waste for the pilot plant tests was anticipated to be 60 wt % chlordane, as received, and 40% kerosene. Therefore, the chlordane waste processed in the bench-scale tests was adjusted to the same composition and contained 43.9 wt % technical chlordane; the elemental composition of the chlordane waste that was processed is shown in Table 6. The chlorine content of this waste was significantly less than that of the HCB-coke mixture. The higher heating value was 32,480 kJ/kg (13,965 Btu/lb). The empirical formula of the chlordane waste that was processed was $C_{5.09}H_{8.70}Cl_{0.78}$.

TABLE 6

ELEMENTAL COMPOSITION OF HCB-COKE AND CHLORDANE-KEROSENE MIXTURES

Element	Composition (wt %)	
	HCB-Coke	Chlordane-Kerosene
C	44.9	61.1
Cl	51.9	27.8
H	1.11	8.7
O	0.28	0.0
Inert	1.8	2.4

TEST CONDITIONS

Basis for Selection of Test Conditions

At the time of the bench-scale tests the baseline (reference) conditions for the pilot-plant tests were planned to be about 1000°C (1832°F), 120% of stoichiometric air, a superficial velocity of about 60 cm/sec (2 ft/sec) in a sodium carbonate melt containing 50 wt % NaCl. The baseline conditions for the bench-scale tests were chosen to match the pilot-plant baseline conditions except for the superficial air velocity and melt composition. The air superficial velocity of 30 cm/sec was chosen for the bench-scale tests because the waste residence time corresponding to this velocity more closely approached the pilot-plant waste residence time in the salt. This is because the quiescent melt depth of the bench-scale unit, about 15 cm (6 in.), is much less than that of the pilot plant, about 122 cm (4 ft). The high chlorine content of the HCB feed (51.9 wt %) and the small fixed amount of melt (~7 kg) in the bench-scale unit led to an extensive increase in NaCl content in the melt. The chlordane-kerosene mixture contained less chlorine (27.8 wt %). In the chlordane tests, the NaCl content of the melt varied less extensively.

Sampling Periods

Each test which generally lasted about two hours consisted of three periods. In the first period, which lasted for about 30 min, a steady-state (with respect to off-gas composition and temperature) was obtained. The particulate loading was determined during this period, but no samples were taken for chemical analyses. In the second period, the off-gas including particulates was bubbled for about 30 min through toluene impinger solution which was then analyzed onsite as soon as the sample was obtained. In the third period, samples were taken for about 30 min for offsite analysis. Five samples, including the filter, the polyurethane foam plugs, the combined toluene impinger solutions, the combined washings of the filter housing, heat exchanger and the sample probe, and the melt samples, were submitted to EMSC. Between the second and third period, air with no fuel was sparged through the melt for 15 min to clean up the melt. No sample was taken during that time.

HCB Test Conditions

The conditions for each test with the HCB-coke mix are given in Table 7. In these tests, a constant composition waste mix consisting of 69.6 wt % HCB and 30.4 wt % coke was used.

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In test No. 1, a blank measurement was taken. The test consisted of sparging air with a superficial velocity of 31 cm/sec (1 ft/sec) through a 20-cm (8 in.) deep bed of pure Na_2CO_3 at 1000°C (1832°F).

TABLE 7

TEST CONDITIONS FOR HCB BENCH-SCALE DESTRUCTION TESTS

Test No.	Type of Test	Temp (°C)	Temp (°F)	% Stoich Air	Waste Feed Rate[a] (kg/h)	Waste Feed Rate[a] (lb/h)	Air Feed Rate (sm^3/h)	Air Feed Rate (scfh)	Nominal NaCl Content of Melt[b] (wt %)
1	Blank	1002	1837	NA[c]	0.0	0.00	4.25	150	0
2	Baseline	1004	1839	118	0.846	1.87	4.25	150	35-39
3	Lower Temp	902	1656	127	0.786	1.74	4.25	150	51-62
4	Minimum Temp	803	1477	111	0.900	1.99	4.25	150	71-76
5	Off-Spec	1009	1848	70	1.440	3.19	4.25	150	86-88

[a] Each kilogram of waste consisted of 0.696-kg HCB and 0.304-kg coke.
[b] During the gas sampling period for offsite analyses.
[c] Not applicable.

Test No. 2 was conducted with the HCB-coke mix under essentially the baseline (reference) conditions, i.e., 1002°C (1837°F), and 118% of stoichiometric air.* The melt initially consisted of pure Na_2CO_3. At the end of that test as a result of the reaction of the chlorine of the HCB with the Na_2CO_3, the melt contained 39 wt % NaCl. During the first 2-1/2 hours, the feeding procedure during combustion was tested. Samples were then taken for both onsite and offsite analyses.

In tests Nos. 3 and 4, the temperature was at 902°C (1656°F) and 803°C (1477°F), respectively. At the end of those tests, the melt contained 62 and 76 wt % NaCl, respectively. The off-gas for tests Nos. 1-4 were sampled for 30 minutes.

---

*100% stoichiometric air is that air required to convert the waste completely to CO_2 and H_2O with no CO, H_2 or excess oxygen being present. The reaction of the waste with Na_2CO_3 must also be considered in calculating the stoichiometry (see Appendix B).

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In test No. 5, the air/waste ratio corresponded to 70% of stoichiometric air. This simulated an off-spec condition such as might be obtained if slugging of the feed occurred or if the air feed rate became inadvertently lowered. This test was conducted at 1009°C (1848°F). By the end of the test, the NaCl content of the melt had reached 88 wt %. The off-gas in this test was sampled for 19 minutes.

Chlordane Test Conditions

The conditions for each test with the chlordane-kerosene feed are given in Table 8. In these tests, a constant composition waste mixture consisting of 43.9 wt % "technical" chlordane and 51.9 wt % kerosene was used.

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TABLE 8

TEST CONDITIONS FOR CHLORDANE BENCH-SCALE DESTRUCTION TESTS

Test No.	Type of Test	Temp		% Stoich Air	Waste Feed Rate[a]		Air Feed Rate		Nominal NaCl Content of Melt[b] (wt %)
		(°C)	(°F)		(kg/h)	(lb/h)	(sm^3/h)	(scfh)	
1	Blank	1000	1832	NA[c]	0.0	0.00	4.25	150	25
2	Reference	999	1830	121	0.414	0.91	4.25	150	29-31
3	900°C	898	1648	118	0.426	0.94	4.25	150	38-39
4	Off-Spec	1002	1836	81	0.618	1.36	4.25	150	52-55

[a] Each kilogram of waste contained 0.439-kg "technical" chlordane.
[b] During the gas sampling period for offsite analyses.
[c] Not applicable.

In test No. 1, a blank run was carried out. The test consisted of sparging air with a superficial velocity of 31 cm/sec (1 ft/sec) through a fresh 15-cm (6 in.) deep bed of Na_2CO_3 containing 25 wt % NaCl at 1000°C (1832°F).

The second test was conducted with the chlordane waste essentially under the baseline reference conditions; specifically, 999°C (1830°F), and 121% of

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stoichiometric air. The melt initially contained 25 wt % NaCl. At the end of that test, the melt contained 31 wt % NaCl.

In test No. 3, the temperature was 898°C (1648°F). The melt contained 39 wt % NaCl at the end of that test. In the last test (No. 4), the air/waste ratio corresponded to 81% of stoichiometric air and was representative of an off-spec condition. This test was conducted at 1002°C (1836°F). By the end of that test, the melt contained 55 wt % NaCl.

The off-gas for the above tests were sampled for 30 minutes.

HCB TEST RESULTS AND DISCUSSION

Destruction Efficiency

The analytical results for HCB destruction are shown in Table 9.* The fourth through the eighth columns show the percentages of the HCB feed which were found in the filter (particulates), washings, the polyurethane foam plug, the impinger, and in the melt. The ninth column (total) is the sum of all these numbers including the melt. The destruction efficiency (next to the last column) is 100% minus this total. The destruction and removal efficiency (DRE) is also included (last column). The destruction and removal efficiency is 100% minus the percent HCB in the feed emitted to the atmosphere. In these tests, the destruction efficiencies and the destruction and removal efficiency were virtually identical since no HCB was detected in any of the melt samples.

Table 10 gives a summary of the results and includes the concentrations of HCB in the off-gas and in the melt.

Excellent destruction was obtained in all cases except in the 800°C test. The best destruction efficiency (>99.9999960%) was obtained at 1000°C (Test 2). This value is considered a conservative value because the destruction efficiency is limited by the detection limits of the impinger and melt

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*Additional details on the analytical results are discussed in Appendix C.

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TABLE 9

DISTRIBUTION OF HCB FROM DESTRUCTION OF HCB-COKE MIX IN BENCH-SCALE TESTS

Test No.	Temp (^oC)	% Stoich Air	Percent of HCB Feed Found in[a]:						Destruction Efficiency[c] (%)	Destruction and Removal Efficiency[d] (%)
			Filter[e]	Washings[e]	Plug[e]	Impinger[e]	Melt[e]	Total[b]		
2	1004	118	0.04×10^{-6}	0.19×10^{-6}	0.04×10^{-6}	$<1.17 \times 10^{-6}$	$<2.55 \times 10^{-6}$	$<3.99 \times 10^{-6}$	>99.9999960	>99.9999986
3	902	127	1.26×10^{-6}	5.43×10^{-6}	18.60×10^{-6}	$<1.35 \times 10^{-6}$	$<3.03 \times 10^{-6}$	29.7×10^{-6}	99.999971	99.999974
4	803	111	157×10^{-6}	$37{,}900 \times 10^{-6}$	$91{,}100 \times 10^{-6}$	4.03×10^{-6}	$<0.48 \times 10^{-6}$	$129{,}000 \times 10^{-6}$	99.87	99.87
5	1009	70	0.53×10^{-6}	13.46×10^{-6}	1.77×10^{-6}	$<2.74 \times 10^{-6}$	$<1.93 \times 10^{-6}$	20.0×10^{-6}	99.999980	99.999982

[a] No HCB was detected when a < symbol is present (except for the total column).
[b] Sum of the percent HCB found in the filter, washings, plug, impinger, and melt.
[c] 100% - total
[d] Destruction and removal efficiency is 100% minus the percent HCB in the feed emitted to the atmosphere.
[e] The analyses of the HCB samples were done in accordance with EPA Method 612.

TABLE 10

SUMMARY OF HCB BENCH-SCALE RESULTS[a]

Test No.	Type of Test	Temp (°C)	% Stoich Air	Conc of HCB in Off-Gas		Conc of HCB in Melt	Destruction Efficiency (%)	Destruction and Removal Efficiency (%)
				(ppmv)	(mg/m^3)	(ppmw)		
2	Baseline	1004	118	<0.00017	<0.0019	<0.0010	>99.9999960	>99.9999986
3	Lower Temp	902	127	0.0028	0.033	<0.0010	99.999971	99.999974
4	Minimum Temp	803	111	15.5	180	<0.00020	99.87	99.87
5	Off Spec	1009	70	0.0031	0.037	<0.00040	99.999980	99.999982

[a] The analyses of the HCB samples were done in accordance with EPA Method 612.

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samples. The HCB contents of these samples are expected to be very low based on the trapping efficiency of the foam plug and the extent of destruction in the melt. Evidence for this expectation is the following:

> The very high efficiency of the polyurethane foam plug for capturing HCB is shown in the 800°C test. In that test, the percent of the HCB feed found in the plug was $91,100 \times 10^{-6}$, while that in the impinger downstream of the plug was only 4×10^{-6}. Thus, it is reasonable to assume that the fraction of HCB found in the impinger is much less than that found in the plug in Test 2. No HCB was found in the melt of the 800°C test, even when the destruction efficiency was only 99.9%.

Thus based on the HCB detected, the destruction efficiency in Test 2 was 99.99999973%.

Excellent destruction efficiencies were also obtained at 900°C (99.999971%) and at 1000°C, 70% of stoichiometric air (99.999980%). In the 900°C test, the greatest percent of the HCB feed was found in the plug followed by the washings. In the off-spec test, the greatest percent was found in the washings.

The relatively low destruction efficiency (99.9%) at 800°C was surprising since earlier destruction efficiencies for tests conducted in this laboratory with PCB's at the same temperature were 99.999%.

No HCB was detected in any melt sample even though the samples were taken while HCB was being fed. Thus, the concentration of HCB in the melt was at most 0.001 ppmw. This is considered significant due to the short residence time of the feed in the expanded melt (~3/4 sec) and is indicative of the rapid kinetics of HCB destruction in the melt.

The concentration of HCB in the off-gas was extremely low in all cases except for the 800°C test. In the baseline test (Test 2), the concentration of HCB was <0.00017 ppmv or <0.0019 mg/m^3. In Tests 3 and 5, the concentrations were higher by an order of magnitude but still extremely low (0.0031 ppmv or 0.037 mg/m^3).

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GC-MS Results

The HCB test samples that were analyzed by the GC-MS are shown in Table 11:

TABLE 11

HCB TEST SAMPLES ANALYZED BY GC-MS

Test No.	Type of Test	Samples
2	Baseline	Filter Foam plug Combined washing Melt sample
3	$900^{o}C$	Foam plug

These samples included all the samples from the reference test (Test 2) except the impinger. They also included the foam plug sample from the $900^{o}C$ test (Test 3). The compounds detected by GC-MS are shown in Table 12. No chlorinated compounds were detected in the reference test. However, at $900^{o}C$, chlorinated benzene compounds, including hexachlorobenzene were detected. The abundance of these chlorinated benzene compounds, as well as that of the nonchlorinated compounds was not determined. Since the concentration of HCB in the off-gas (determined by GC-EC) was only 3 ppb, it is estimated that the concentrations of the other chlorinated compounds were also in the ppb range. It is not clear whether the nonchlorinated materials originated from the HCB or from the coke which contained a considerable amount of tar.

Off-Gas Composition

The off-gas compositions are shown in Table 13. No chlorine or phosgene was detected in the off-gas. The limits of detection of chlorine and phosgene are 0.2 and 0.3 ppmv, respectively. The HCl concentrations, determined by the Drager tube method, were 100 ppm in Tests 2, 3, and 5. However, after Test 3, a blank (sparging of air only through the NaCl-containing melt) yielded the same 100 ppm. This suggests that NaCl in the melt may affect the Drager tube

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TABLE 12

RESULTS OF GC-MS ANALYSES OF HCB TEST SAMPLES

Test No.	Sample	Compound
2	Filter	3-methyl hexane
		Heptane
		Methylcyclohexane
		Toluene
		Naphthalene
	Foam Plug	Benzene
		Heptane
		Toluene
		Naphthalene
		Acenaphthalene
	Washings	Ethylbenzene
		Di-methylbenzene
	Melt	Cyclohexane
		3-methyl hexane
		Heptane
		Methylcyclohexane
3	Foam Plug	Dichlorobenzene
		Trichlorobenzene
		Tetrachlorobenzene
		Pentachlorobenzene
		Hexachlorobenzene
		Naphthalene
		Methylnaphthalene
		Chloronaphthalene
		Phthalates

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TABLE 13

OFF-GAS COMPOSITION FROM DESTRUCTION OF HCB-COKE MIXTURE IN BENCH-SCALE TESTS

Test No.	Type of Test	Average Composition of Off-Gas												Particulate Loading[a]	
		(vol %)					(ppmv)								
		O_2	Ar	N_2	CO_2	CO	Cl_2[b]	Phosgene[b]	HCl	NO_x	H_2	CH_4	HC[c]	(gr/scf)	(g/sm^3)
2	Baseline	3.1	0.9	75.4	18.6	1.3	<0.2	<0.3	<100	46	<100[b]	<20[b]	31	3.3	7.6
3	Lower Temp	4.3	0.9	75.0	16.9	2.2	<0.2	<0.3	<100	17	<100[b]	<20[b]	50	1.5	3.5
4	Minimum Temp	7.1	0.9	74.2	15.6	2.4	<0.2	<0.3	<400	30	<100[b]	<20[b]	14	4.0	9.2
5	Off-Spec	0.0	0.8	67.1	15.1	14.4	<0.2	<0.3	<100	NA[d]	18,000	365	NA	13.1	30.1

[a] The bench-scale unit has no provisions for removing particulates.

[b] Not detected

[c] Unburned hydrocarbons

[d] Not analyzed

measurements of HCl. The retention of the chlorine by the melt was very good. To illustrate, if all the hydrogen in the feed combined with the chlorine to form HCl and the remaining chlorine formed either Cl_2 or phosgene ($COCl_2$), the HCl and combined Cl_2 and phosgene concentrations in the off-gas would have been 58,000 and 9,200 ppm, respectively. Traces of HCl were detected in the 800°C test. A pungent odor resembling that of HCl was noted in this particular test, whereas there was none in the other tests.

Neither H_2 or CH_4 was detected except under deficient air conditions (Test 5). As expected, the NO_x levels were very low (<50 ppm).

The CO levels were higher than desired (1.3-2.4%) in the excess air tests. Such high values have been noted before in this laboratory when chlorinated aromatic compounds were destroyed in Na_2CO_3 melts containing NaCl. Using more excess air resulted in lower CO emissions. For example, during Test 2, the CO content was only 0.55% when the off-gas contained 5.5% O_2 (i.e., 137% of stoichiometric air).

The particulate loadings were relatively high because the bench-scale unit has no provisions for removing particulates. In the pilot plant and in a commercial plant, particulate removal devices such as fabric filters would be incorporated into the system. The particulates at 1000 and 900°C were due mainly to volatilizing NaCl. At 800°C, volatility of NaCl would be expected to be less. Thus, the higher particulate loading at 800°C was presumably due to unburned carbon.

Problems were encountered with feeding the HCB. The material would tend to pack in the hopper, resulting in a nonflowing mass. This problem was attributed in part to the small-size bench-scale unit. It was found that the vibrator attached to the hopper aggravated the packing problem. However, incorporating a hand-driven stirrer into the hopper solved the problem sufficiently well to allow a satisfactory test to be completed.

CHLORDANE TEST RESULTS AND DISCUSSION

Destruction Efficiency*

The analytical results for chlordane destruction are shown in Table 14. The fourth through the ninth columns show the percent of the chlordane feed which was found in the filter (particulates), washings, the two polyurethane foam plugs, the impinger, and in the melt. The tenth column (total) is the sum of all these numbers including the melt. The destruction efficiency (next to the last column) is 100% minus the total. The destruction and removal efficiency (DRE) is given in the last column.

Since the sensitivity of the gas chromatograph with its electron capture detector was significantly less for chlordane (60 ng/ml) than it was for HCB (1 ng/ml), the chlordane detection limits were considerably higher than for those of HCB.

Technical-grade chlordane, which was the material used in these tests and which was the material available for standards, is a mixture consisting of 60-75% chlordane and 25-40% related compounds. A gas chromatogram of this chlordane is given in Figure 13. From this figure it can be seen that chlordane gives a much more complicated chromatogram than HCB which has only a single peak. In this work, the analytical technique used was essentially that of pattern recognition. This technique is based on the fact that the gas chromatogram of chlordane has a unique elution pattern. The four major peaks at retention times of approximately 2.6, 4.2, 6.3, and 8.0 min were used for identifying chlordane. Positive identification would be assumed when all four peaks were observed. However, the technique of pattern recognition was complicated by interferences and by the fact that the combustion process probably altered the pattern. In no case were all four peaks observed in the samples; thus positive identification by pattern recognition could not be made. In the samples that contained from one to three peaks with the above retention time,

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*Additional details on the analytical results are discussed in Appendix C.

TABLE 14

DISTRIBUTION OF CHLORDANE FROM DESTRUCTION OF CHLORDANE-KEROSENE WASTE IN BENCH-SCALE TESTS

Test No.	Temp (°C)	% Stoich Air	Percent of Chlordane Found in[a]:							Destruction Efficiency[c] (%)	Destruction and Removal Efficiency[d] (%)
			Filter	Washings	Plug No. 1	Plug No. 2	Impinger	Melt	Total[b]		
2	999	121	$<2.4 \times 10^{-6}$	$<7.5 \times 10^{-6}$	$<4.8 \times 10^{-6}$	$<4.8 \times 10^{-6}$	$<29.6 \times 10^{-6}$	$<56.4 \times 10^{-6}$	$<105.5 \times 10^{-6}$	>99.99989	>99.999951
3	898	118	$<4.6 \times 10^{-6}$	$<55.9 \times 10^{-6}$	$<4.6 \times 10^{-6}$	$<4.6 \times 10^{-6}$	$<27.9 \times 10^{-6}$	$<46.6 \times 10^{-6}$	$<144.2 \times 10^{-6}$	>99.99986	>99.999903
4	1002	81	$<1013 \times 10^{-6}$	$<3282 \times 10^{-6}$	$<2250 \times 10^{-6}$	$<7 \times 10^{-6}$	$<21 \times 10^{-6}$	$<48 \times 10^{-6}$	$<6621 \times 10^{-6}$	>99.9934	>99.9934

[a] The analyses of the chlordane samples were done in accordance with EPA Method 608.

[b] Sum of the percent chlordane found in the filter, washings, two plugs, impinger, and melt.

[c] 100% − total.

[d] Destruction and removal efficiency is 100% minus the percent chlordane in the feed emitted to the atmosphere.

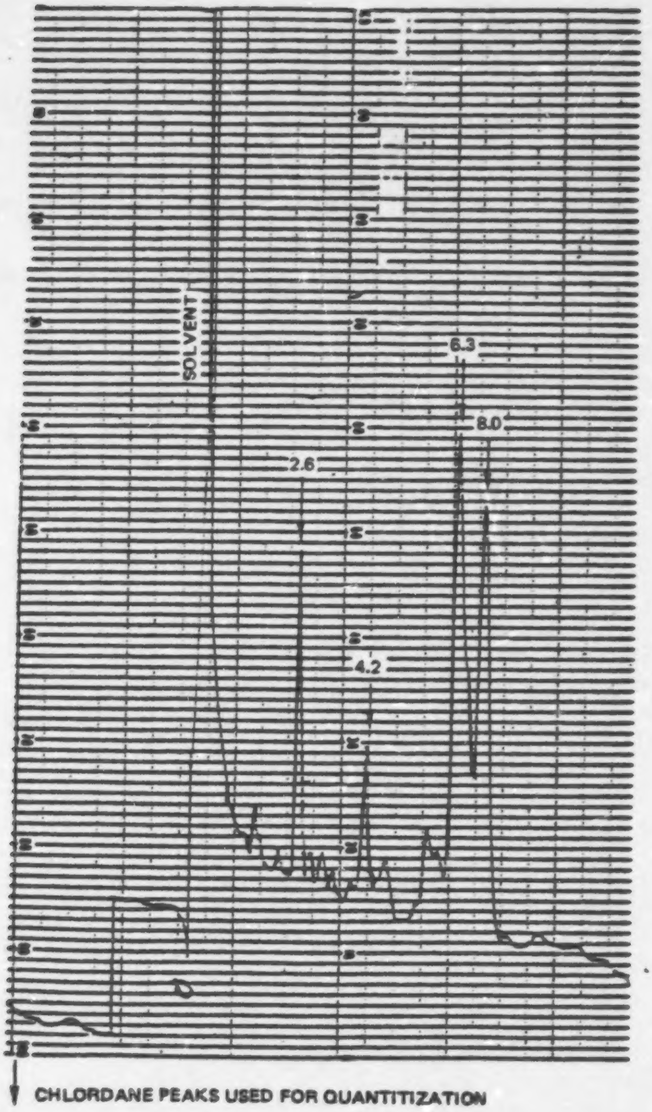

Figure 13. Gas chromatogram of technical grade chlordane standard

an upper limit of the chlordane concentration was determined based on these detected peaks. This was done by calculating for each peak, the amount of chlordane that would be present, if indeed the detected peaks were actually due to chlordane. The average of the observed "chlordane peaks" was then reported as a maximum value.

Excellent chlordane destruction was obtained in Tests 2 and 3. In these tests, two peaks with the same elution times as two of the four characteristic chlordane peaks were present. These peaks were assumed to be chlordane which led to destruction efficiencies and destruction and removal efficiencies of >99.9999%.

In the off-spec test, in which larger peaks were found, three peaks with the same elution time as three of the four characteristic chlordane peaks were present in all samples except the impinger and the melt sample. However, when the first plug was examined by GC-MS, the three peaks with elution times similar to chlordane were identified as not due to chlordane isomers. Thus, the chlordane destruction efficiencies were probably much greater than 99.99%, which was calculated assuming the three "chlordane" peaks were actually due to chlordane.

Table 15 gives a summary of the results and includes the concentrations of chlordane in the off-gas and in the melt. No chlordane was detected in any melt sample even though melt samples were taken while the chlordane was being fed. Thus, the concentration of chlordane in the melt was, at most, 12 ppb.

The concentration of chlordane in the off-gas was very low. In the reference test (Test 4) and in the 900^{0}C test (Test 3), the concentration of chlordane was <0.001 and <0.003 ppm, respectively. The concentration of chlordane during the off-spec test was 0.243 ppm. However, the fact that the peaks (at least in the plug) could not be confirmed as chlordane by the GC-MS indicates that the chlordane concentration is much less than this value.

TABLE 15

SUMMARY OF CHLORDANE BENCH-SCALE RESULTS[a]

Test No.	Type of Test	Temp (°C)	% Stoich Air	Conc of Chlordane in Off-Gas		Conc of Chlordane in Melt	Destruction Efficiency (%)	Destruction and Removal Efficiency (%)
				(ppmv)	(mg/m^3)	(ppmw)		
2	Baseline	999	121	<0.0013	<0.022	<0.0086	>99.99989	>99.999951
3	900°C	898	118	<0.0027	<0.045	<0.0072	>99.99986	>99.999903
4	Off-Spec	1002	81	<0.24	<4.18	<0.012	>99.9934	>99.9934

[a] The analyses of the extracted chlordane samples were done in accordance with EPA Method 608.

GC-MS Results--

The chlordane test samples that were analyzed by the GC-MS are shown in Table 16:

TABLE 16

CHLORDANE TEST SAMPLES ANALYZED BY GC-MS

Test	Type of Test	Samples
2	Baseline	Filter Foam Plug 1 Foam Plug 2 Combined Washings Melt Sample
4	Off-Spec	Foam Plug 1

These samples included all the samples from the baseline test (Test 2) except the impinger. They also included the first foam plug from the off-spec test (Test 4). The compounds detected by GC-MS are shown in Table 17. No chlorinated organic compounds were detected in any of the samples.

However, polynuclear aromatic hydrocarbon compounds were detected in the plug of the off-spec tests. Two polynuclear aromatic standard (fluorene and fluoranthene) were analyzed under the same GC-MS conditions as those performed for the samples in Table 16. The total amount of fluorene and fluoranthene in the plug of Test 4 was determined to be 0.1 mg and 0.9 mg, respectively. These values correspond to off-gas concentrations of 1.16 mg/m^3 and 10.5 mg/m^3 for fluorene and fluoranthene, respectively. The abundance of the remaining peaks was not determined. It is not clear whether the compounds originated from the chlordane or from the kerosene.

Off-Gas Composition--

The off-gas compositions are shown in Table 18. No chlorine or phosgene was detected in the off-gas. The limits of detection of chlorine and phosgene were 0.2 and 0.3 ppmv, respectively. The HCl concentrations, determined by

TABLE 17

RESULTS OF GC-MS ANALYSES OF CHLORDANE TEST SAMPLES

Test No.	Sample	Compound
2	Filter	Toluene
		C_8 Compound
		C_6 alcohol
		Nonanal
		Decanal
		Diethylphthalate
		Hexadecanoic acid
	Plug 1 (upstream)	Toluene
		C_6 alcohol
	Plug 2 (downstream)	Toluene
		C_8 Compound
		C_6 alcohol
		Diethylphthalate
		Phenanthrene
		Hexadecanoic acid
	Probe Wash	No significant peaks
	Melt	Methyl benzene
		Ethyl benzene
		2, 2-dimethyl 3-propyloxirane
		3, 4-dimethyl 2-hexanol
		1, 2, 3 propanetriol triacetate
		Undecane
4*	Foam Plug 1 (upstream)	Methylnaphthalene
		Biphenylene
		Acenaphthalene
		Dibenzofuran
		9H-Fluorene
		Indene
		Phenyl Naphthalene
		Fluoranthene
		Pyrene

*Off-spec condition

TABLE 18

OFF-GAS COMPOSITION FROM DESTRUCTION OF CHLORDANE-KEROSENE MIXTURE WITH BENCH-SCALE TESTS

Test No.	Type of Test	Average Composition of Off-Gas												Particulate Loading[a]	
		(vol %)					(ppmv)								
		O_2	Ar	N_2	CO_2	CO	Cl_2[b]	Phosgene[b]	HCl	NO_x	H_2	CH_4	HC[c]	(gr/scf)	(g/sm^3)
2	Baseline	3.8	0.9	82.2	13.7	0.04	<0.2	<0.3	<100	35	<100	<20	8	5.0	11.5
3	900°C	3.5	0.9	81.5	13.2	1.2	<0.2	<0.3	<100	26	<100	<20	825	1.6	3.7
4	Off-Spec	0.0	0.9	76.0	15.0	3.3	<0.2	<0.3	<100	NA[d]	1.8%	0.4%	NA	8.9	20.5

[a] The bench-scale unit has no provisions for removing particulates.

[b] Not detected

[c] Unburned hydrocarbons

[d] Not analyzed

the Drager tube method, were 100 ppm. However, a blank (sparging of air only through the NaCl-containing melt) after tests yielded the same 100 ppm. This suggests that NaCl in the melt may affect the Drager tube measurements of HCl.

Neither H_2 nor CH_4 were detected except under the off-specification conditions (Test 4). As expected, the NO_x levels were very low (<50 ppm).

The CO and unburned hydrocarbon concentrations were considerably higher at 900°C than at 1000°C. The temperature effect was studied more closely after Test 3. The results are shown in Table 19. The effect of increasing temperature on hydrocarbon emissions is dramatic. As the temperature increased from 906°C to 950° to 1004°C, the hydrocarbon concentrations in the off-gas decreased from 900 to 560 to 10 ppm, respectively. The effect of increasing temperature on CO emissions was less dramatic but still significant.

TABLE 19

EFFECT OF TEMPERATURE ON CO AND HYDROCARBON EMISSIONS IN BENCH-SCALE TESTS

% O_2	Temp (°C)	% Stoich Air	CO (%)	HC (ppm)
3.5	906	115	1.1	900
3.8	908	117	1.3	800
3.8	913	117	1.2	700
3.9	921	119	1.0	580
3.8	930	119	1.0	650
3.2	950	115	0.9	560
2.9	960	114	0.7	500
3.2	970	115	0.7	400
3.1	980	115	0.5	150
3.2	985	115	0.5	140
3.0	990	118	0.4	140
2.7	994	113	0.3	140
4.4	995	125	0.2	50
4.7	1004	127	0.1	3
2.5	1004	112	0.2	60
3.4	1004	118	0.1	10

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The effect of stoichiometry on CO and hydrocarbon emissions was studied at 900°C. The results are shown in Table 20. The effect of stoichiometry on hydrocarbon emission was again dramatic. The hydrocarbon emissions decreased from 900 to 45 to 2 ppm as the percent of stoichiometric air increased from 115 to 143 to 241%, respectively. The CO decrease was again less dramatic but still significant.

TABLE 20

THE EFFECT OF STOICHIOMETRY ON CO AND HYDROCARBON EMISSIONS IN BENCH-SCALE TESTS

% O_2	% Stoich Air	Temp (°C)	CO (%)	HC (ppm)
3.5	115	899	1.2	900
3.9	118	903	1.2	850
4.1	120	904	1.2	650
6.8	143	898	0.5	45
7.2	147	900	0.5	45
9.0	170	905	0.3	14
9.3	174	902	0.3	10
12.4	235	900	0.2	2
12.6	241	902	0.2	2

EVALUATION OF BENCH-SCALE TEST RESULTS

The results of these tests showed that destruction efficiencies and destruction and removal efficiencies of 99.9999% and better could be achieved on the bench-scale level with HCB and chlordane by using the Molten Salt Destruction process. The analytical techniques and process performance data demonstrated in this program proved to be very valuable in the pilot-plant program.

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HCB

Increasing temperature resulted in better destruction. While destruction was excellent at temperatures as low as 900°C, process limits identified at 800°C, at least with coke as the auxiliary fuel, suggested that the temperature should not be permitted to decrease below 900°C in the pilot-plant test program. A temperature of about 1000°C was preferred since no detectable amounts of chlorinated degradation products were observed at that temperature.

Chlordane

Destruction efficiency and destruction and removal efficiencies of 99.9999% and better could be achieved on the bench-scale level at 1000°C and at 900°C. A temperature of 1000°C was preferred over 900°C since CO and hydrocarbon emissions were much lower at the higher temperature. For the same reason, more excess air was recommended. In addition, the concentration of degradation products should be lowered with more excess air. Off-specification conditions such as <100% of stoichiometric air should be avoided to reduce the emissions of polynuclear aromatic hydrocarbons.

Analytical Procedure

Since the polyurethane foam plugs were so efficient in capturing the HCB and chlordane, it was recommended for the pilot-plant tests that the second plug (used for chlordane tests) and the impingers be eliminated for offsite analyses.

SECTION 7

PILOT-SCALE TESTS

TEST DESCRIPTION

Waste Streams

Prior use of the Molten Salt Test Facility has demonstrated the need for auxiliary fuel to prevent plugging of the feed systems by salt deposits. (Note that this is not necessarily characteristic of MSD systems but is a peculiarity of the MSTF system.) The waste stream compositions are described below.

The elemental compositions of the waste feeds with the auxiliary fuel coke* are given in Table 21. Auxiliary fuel coke was fed with the as-received HCB and chlordane to avoid freezing the salt injection nozzles.

Sequence of Tests

The sequence of test runs was: HCB Run 1; chlordane Runs 1, 2A, 2B, 3, and 4. The rest of the HCB tests were then completed with Runs 2A, 2B, 3A, and 3B. Feed system modifications (see Page 70) were required to resolve difficulties with the HCB "rat-holing" and bridging in the hopper. Thus, testing of chlordane was initiated after the first HCB run to insure effective use of the facility during these modifications. Testing was done in 0.5-2.0-h test periods with a minimum 1 h of vessel purging and up to 3 h of process stabilization between sampling periods. Destructor gas sampling was done during each sampling period. Process data such as off-gas composition were

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*The HCB and coke were fed together; however, the liquid chlordane and coke were fed through separate nozzles.

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TABLE 21

COMPOSITIONS OF THE WASTE FEEDS WITH COKE

Waste	Test No.	Wt % Waste	Wt % Coke	Elemental Composition (wt %) C	H	Cl	O	Empirical Formula
HCB	1	51.2	48.8	58.3	1.87	39.4	0.40	$C_{6.00}H_{2.30}Cl_{1.37}$
HCB	2A[a]	50.5	49.5	58.7	1.89	38.9	0.41	$C_{6.00}H_{2.31}Cl_{1.34}$
HCB	2B[a]	65.5	34.5	48.5	1.31	49.9	0.28	$C_{6.00}H_{1.94}Cl_{2.08}$
HCB	3A[a]	72.3	27.7	43.8	1.04	54.9	0.22	$C_{6.00}H_{1.71}Cl_{2.54}$
HCB	3B[a]	100.0	0.0	25.2	0.00	74.8	0.00	$C_{6.00}Cl_{6.00}$
Chlordane	1	33.8	66.2	78.4	4.35	16.6	0.56	$C_{6.00}H_{4.00}Cl_{0.43}$
Chlordane	2A[a]	64.3	35.7	63.7	4.74	31.3	0.30	$C_{6.00}H_{5.36}Cl_{1.00}$
Chlordane	2B[a]	78.1	21.9	57.0	4.90	37.9	0.39	$C_{6.00}H_{6.19}Cl_{1.35}$
Chlordane	3	56.7	43.3	67.3	4.65	27.6	0.36	$C_{6.00}H_{4.97}Cl_{0.83}$
Chlordane	4	74.3	25.7	58.8	4.85	36.1	0.21	$C_{6.00}H_{5.93}Cl_{1.25}$

[a] In the HCB tests, A and B in Tests 2 and 3 denote two different feed conditions which were imposed without stopping the test. Analytical results were obtained in both A and B tests.

[b] In chlordane Test 2, a low feed rate was obtained (2A) which was similar to that of Test 1; a higher rate was obtained in Test 2B. Chemical analyses were obtained in both tests.

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taken during this time. Auxiliary fuel was used throughout the various waste burn periods as required to maintain nominal operating conditions. Between burn periods, coke or diesel oil was the only combustible material fed to the vessel.

Test Conditions

The baseline (reference) molten salt destructor conditions considered optimal for waste destruction were 1000°C (1832°F) bed temperature, 120% of stoichiometric air, a superficial air velocity of 0.60 m/s (2.0 fps), and a salt melt composition of nominally 50 wt % NaCl and 50 wt % Na_2CO_3. The test conditions selected deviated from some of these values to challenge system limits and to provide a better appreciation of the effect of changing the critical process variables and also to provide a better data base for further expanding the application of molten salt destruction to other wastes.

Pilot-scale test operation was conducted on a continuous, round-the-clock basis to minimize the number of time-consuming startup-shutdown sequences of the MSTF refractory lined destructor vessel. This method of test operation, however, precluded the determination of accurate mass balances for each test run. Carbon balances were determined for each test on the basis of measurements of waste feed rates and auxiliary fuel feed rates, and with measurements of the gas flow rates and off-gas compositions. The carbon balances are presented in Section 8.

HCB Tests--

The process conditions for the HCB tests are shown in Table 22. The melt temperatures varied from 918°C (1685°F) to 985°C (1805°F). The HCB feed rate generally increased with each succeeding test and ranged from 21 kg/h (47 lb/h) to 122 kg/h (269 lb/h). Auxiliary coke fuel was added to the HCB feed (which had a heating value of only 8,304 kJ/kg or 3570 Btu/lb) in all but the last test in order to provide enough heat to maintain the melt temperature. In the last test, the HCB at a feed rate of 122 kg/h provided enough heat to prevent excessive lowering of the melt temperature during the sampling period. For an

TABLE 22

TEST CONDITIONS FOR HCB PILOT-SCALE DESTRUCTION TESTS

Test No.	Effect Studied	Temp		% Stoich Air	Solid Feed Rates						Air Feed Rate		% of Total Thermal Load	
					HCB*		Coke		Salt**					
		(^{o}C)	(^{o}F)		(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(sm^3/h)	(scfh)	HCB	Coke
1	Low feed rate	969	1777	134.6	21.4	47.2	20.4	45.0	24.7	54.5	319	11,280	20.2	79.8
2A	Low feed rate	958	1757	140.1	20.9	46.0	20.4	45.0	68.1	150	331	11,700	19.7	80.3
2B	Lowest temperature	918	1685	140.7	34.4	75.8	18.2	40.0	68.1	150	331	11,700	31.4	68.6
3A	Higher feed rate	982	1800	120.1	50.8	112	19.5	43.0	43.3	95.5	331	11,700	38.5	61.5
3B	Highest feed rate	985	1805	150.5	122	269	0	0	28.5	63	331	11,700	100.0	0.0

*A total of 222 kg (488 lb) of HCB was fed during the test series

**50 wt % Na_2CO_3-50 wt % NaCl

extended test, auxiliary fuel would have been necessary. The percent of the total thermal load provided by the HCB and by the coke is given in the last two columns. The percentage of the total thermal load provided by the HCB ranged from 19.7 to 100%.

Combustion air to the vessel consisted of a constant 170 sm^3/h (6000 scfh) primary air preheated to 650^oC (1200^oF) plus the various ambient conveying and sweep air streams. The total air feed rate was in general 331 sm^3/h (11,700 scfh). All of the runs were made at a superficial gas velocity in the melt of about 0.80 m/s (2.6 fps). The above conditions resulted in stoichiometric air/HCB-coke combustion ratios, measured on the basis of air, HCB, and coke feed rates ranging from 1.20 to 1.51.

The molten salt bed composition was adjusted to a nominal 50 wt % Na_2CO_3/50 wt % NaCl before each test and was maintained at that value ±5 wt % during the tests. The salt feed consisted of a 50 wt % Na_2CO_3-50 wt % NaCl mixture. This feed was added to (1) provide continuous overflow, (2) remove excess heat, and (3) add makeup Na_2CO_3. In order to accomplish these three purposes, the Na_2CO_3 feed rates were sometimes greater than necessary to simply provide makeup salt to react with the chlorine and were sometimes lower. In a system designed specifically for chlorinated waste disposal, the Na_2CO_3 would be added without NaCl. Further, it would be added to provide makeup Na_2CO_3 only.

Difficulties with the HCB flowing in the feed system hopper were encountered with the first run and so the chlordane test series was initiated at that time while modifications to the hopper were made. These modifications included addition of two air blast product "Fluffers" to collapse bridging and ratholes, a pneumatic vibrator to enhance flowability, and a rodding device under the rotary valves to break up clumps of caked HCB. HCB test runs 2A, 2B, 3A, and 3B were completed on the last day of testing after the chlordane tests were completed. The changes made to the hopper system were not completely satisfactory, however, and large variations from the reported (average) HCB feedrates occurred at times during all of the HCB runs. These variations resulted in major fluctuations in the off-gas GC readings.

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The duration of the tests for tests 1, 2A, 2B, 3A, and 3B were 134, 18, 21, 11, and 20 minutes, respectively. The sampling times for tests 1, 2B, and 3B were 23, 19, and 20 minutes, respectively.

Chlordane Tests--

The process conditions for the chlordane tests are shown in Table 23. The melt temperature was varied to a somewhat greater extent than in the case of HCB; it ranged from 896°C (1645°F) to 991°C (1816°F). The chlordane feed rate generally increased with each succeeding test and ranged from 12 kg/h (27 lb/h) to 33 kg/h (72 lb/h).

Auxiliary coke fuel was added to the salt makeup in all tests except for HCB Test 3B. The coke was added with the salt makeup to prevent the conveying air from freezing the melt at the salt nozzle exit. The percent of the total thermal load provided by the chlordane and by the coke is given in the last two columns.

The total air feed rate and the superficial gas velocity were similar to those of the HCB tests. The above conditions resulted in stoichiometric air/chlordane-coke ratios, measured on the basis of air, chlordane, and coke feed rates ranging from 0.74 to 1.38. Test 3 was a test which involved an off-specification condition — namely deficient air.

The molten salt bed composition was 50 wt % Na_2CO_3 and 50 wt % NaCl.

The duration of the tests for tests 1, 2A, 2B, 3, and 4 were 120, 67, 90, 71, and 92 minutes, respectively. The corresponding sampling times for these tests were: location 1-21, 20, 29, 20, and 23 minutes; location 2-60, 60, 85, 60, and 60 minutes, respectively.

Between burn periods, coke or diesel oil was the only combustible material fed to the vessel for both HCB and chlordane tests. The combustor was operated for a total of approximately 96 h at temperature during the course of the program.

TABLE 23

TEST CONDITIONS FOR CHLORDANE PILOT-SCALE DESTRUCTION TESTS

Test No.	Effect Studied	Temp		% Stoich Air	Liquid and Solid Feed Rates						Air Feed Rate		% of Total Thermal Load	
					Chlordane*		Coke		Salt**					
		(^oC)	(^oF)		(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(sm^3/h)	(scfh)	Chlordane	Coke
1	Low feed rate	982	1799	102.7	12.1	26.7	23.6	52.4	103	227	307	10,860	21.2	78.8
2A	Higher feed rate	961	1762	116.1	24.6	54.1	13.6	30.0	44.4	97.8	307	10,860	47.9	52.1
2B	Lower temperature	933	1712	122.6	30.8	67.8	8.62	19.0	NM***	NM***	307	10,860	65.3	34.7
3	Deficient air	991	1816	74.1	32.7	72.0	25.0	55.0	113	250	307	10,860	40.8	59.2
4	Lowest temperature	896	1645	138.2	25.0	55.0	9.62	19.0	0	0	307	10,860	60.6	39.4

*A total of 121 kg (455 lb) of chlordane was fed during the test series

**50 wt % Na_2CO_3-50 wt % NaCl

***Not measured

TEST RESULTS

The results associated with the destruction of HCB and chlordane are discussed first. This is followed by a brief discussion on the PICS (products of incomplete destruction). A discussion of the combustion products concludes this section.

Destruction Results

The destruction results for HCB and chlordane are shown in Tables 24 and 25, respectively. The top half of each table shows the results from Sample Location 1 which is just downstream of the destructor vessel and thus gives an indication of the performance of the molten salt. The lower half of each table shows the results from Sample Location 2 which is downstream of the baghouse and thus gives an indication of the performance of the entire destruction system.

The concentration of HCB or chlordane in the off gas (Columns 3 and 4), and the value for the percent of HCB (or chlordane) feed found in the off-gas (Column 6) from Sample Location 1 include the contributions from (a) particulates, (b) the probe wash as well as, (c) that from the gas passing through the glass fiber filter. The destruction efficiency (next to the last column) measured at Sample Location 1) is given by 100% minus the sum of the percent of HCB or chlordane found in the off-gas and that found in the melt. The destruction and removal efficiency (last column) measured at Sample Location 1 is given by 100% minus the percent of HCB or chlordane found in the off-gas.

The concentration of HCB or chlordane in the stack gas and the value for the percent of HCB (or chlordane) feed found in the stack gas, both measured at Sample Location 2, do not include the contribution of particulates. Only the values of DRE are given at this sample location.

The use of approved quality assurance and control procedures (described in Section 5) support the validity of the reported destruction and removal efficiencies in the range of 5-8 9's as related to the destructor vessel. The

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TABLE 24
PILOT-SCALE HCB DESTRUCTION RESULTS

Test No.	HCB Feed Rate (kg/h)	Sample Location 1						
		Concentration of HCB in Off-Gas[a]		Conc'n of HCB in Melt[a] (ppmw)	% of HCB Feed Found in[a]		Destruction Efficiency (%)	Destruction and Removal Efficiency (%)
		(ppmv)	(mg/m^3)		Off-Gas	Melt		
1	21.4	2.4×10^{-5}	2.7×10^{-4}	NM[b]	0.39×10^{-6}	NM[b]	NM[b]	8-9's 61[c]
2A	20.9	$<7.0 \times 10^{-5}$	$<8.0 \times 10^{-4}$	NM[d]	$<1.3 \times 10^{-6}$	NM[d]	NM[d]	>7-9's 87
2B	34.4	2.0×10^{-3}	2.2×10^{-2}	0.001	21×10^{-6}	4.1×10^{-6}	6-9's 74	6-9's 79
3A	50.8	$<1.1 \times 10^{-4}$	$<1.3 \times 10^{-3}$	NM[d]	$<0.84 \times 10^{-6}$	NM[d]	NM[d]	>8-9's 19
3B	122	6.3×10^{-3}	7.1×10^{-2}	0.10	19×10^{-6}	230×10^{-6}	5-9's 77	6-9's 81

Test No.	HCB Feed Rate (kg/h)	Sample Location 2			
		Concentration of HCB in Stack Gas		% of HCB Feed Found in Stack Gas	Destruction and Removal Efficiency (%)
		(ppmv)	(mg/m^3)		
1	21.4	$<5.2 \times 10^{-7}$	$<6.0 \times 10^{-6}$	$<9 \times 10^{-9}$	>10-9's 09[c]
2B	34.4	$<2.4 \times 10^{-6}$	$<2.7 \times 10^{-5}$	$<2.7 \times 10^{-8}$	>9-9's 73
3B	122	9.4×10^{-6}	1.6×10^{-4}	4.4×10^{-8}	9-9's 56

[a] < symbol indicates no HCB detected

[b] Not measured because no overflow took place during sampling period

[c] 8-9's 61 denotes 99.99999961%; 10-9's 09 denotes 99.9999999909%

[d] Samples taken only for on-site analyses; did not include melt samples

TABLE 25
PILOT-SCALE CHLORDANE DESTRUCTION RESULTS

Test No.	Chlordane Feed Rate (kg/h)	Sample Location 1							
		Concentration of Chlordane in Off Gas		Conc'n of Chlordane in Melt[b] (ppmw)	% of Chlordane Feed Found in[b]		Destruction Efficiency (%)	Destruction and Removal Efficiency (%)
		(ppmv)	(mg/m^3)		Off-Gas	Melt		
1	12.1	3.5×10^{-3}	5.9×10^{-2}	<0.005	170×10^{-6}	$<2.6 \times 10^{-5}$	5-9's 81[a]	5-9's 83
2A	24.6	2.1×10^{-3}	3.5×10^{-2}	<0.004	43×10^{-6}	$<2.0 \times 10^{-5}$	6-9's 37	6-9's 55
2B	30.8	4.1×10^{-3}	6.8×10^{-2}	<1.2	68×10^{-6}	$<3.0 \times 10^{-3}$	>4-9's 70	6-9's 32
3	32.7	3.4×10^{-4}	5.7×10^{-3}	<1.2	5.3×10^{-6}	$<3.9 \times 10^{-3}$	>4-9's 61	7-9's 47
4	25.0	3.2×10^{-4}	5.3×10^{-3}	<0.43	6.5×10^{-6}	$<1.4 \times 10^{-3}$	>4-9's 85	7-9's 34

Chlordane Test No.	Chlordane Feed Rate (kg/h)	Sample Location 2			
		Concentration of Chlordane in Stack Gas[b]		% of Chlordane Found in Stack Gas	Destruction and Removal Efficiency (%)
		(ppmv)	(mg/m^3)		
1	12.1	$<2.5 \times 10^{-5}$	$<4.1 \times 10^{-4}$	$<1.2 \times 10^{-6}$	>7-9's 88[a]
2A	24.6	$<3.1 \times 10^{-5}$	$<5.1 \times 10^{-4}$	$<0.64 \times 10^{-6}$	>8-9's 36
2B	30.8	$<2.2 \times 10^{-5}$	$<3.6 \times 10^{-4}$	$<0.36 \times 10^{-6}$	>8-9's 64
3	32.7	$<2.7 \times 10^{-4}$	$<4.4 \times 10^{-3}$	$<4.1 \times 10^{-6}$	>7-9's 59
4	25.0	$<4.7 \times 10^{-5}$	$<7.8 \times 10^{-4}$	$<0.86 \times 10^{-6}$	>8-9's 14

[a] 5-9's 81 denotes 99.99981%; 7-9's 88 denotes 99.9999988%

[b] <symbol indicates no chlordane detected

extensive increase in sampling volumes (~10X) of gas downstream of the baghouse coupled with the lower detection limits achieved for these samples, especially for HCB, resulted in the overall system DREs ranging as high as 10-9's for HCB and 8-9's for chlordanes. The lower detection limits (as compared to those for vessel off-gas samples) were due to cleaner samples and concomitantly reduced interferences in the GC-EC analyses of gas samples taken downstream of the baghouse.

HCB Destruction--

Destruction and Removal Efficiency (DRE)*--The DREs measured at Sampling Location 1 were greater than 6-9's (>99.9999%) in all 5 tests, even when the HCB feed rate was as high as 122 kg/h (269 lb/h). In Tests 1 and 3A, the DRE was as high as 8-9's. Thus, the salt melt was very effective in producing an off-gas essentially free of HCB even at a melt temperature as low as 918°C (1685°F) where the DRE was almost 7-9's (Test 2B).

The DREs measured at Sampling Location 2 represent the performance of the entire system; they were much greater than those measured at Location 1. In the three tests in which DREs were measured, the DRE values were 9-9's and greater. No HCB was detected in the stack gas in Tests 1 and 2B. However, in Test 3B where the HCB feed rate was relatively high, a trace of HCB (9.4 x 10^{-6} ppmv) was detected in the stack gas.

The greater DREs in Sampling Location 2 than in Location 1 (by a factor of 15 to 1,000) were a result of the removal of HCB particulates by the baghouse and/or the settling out of HCB particulates in the piping between the two sampling positions. Data are not available to determine which of these two reasons for the enhanced DREs was predominant.

Destruction Efficiency--The DE at Sampling Location 1 differed from the DRE values due to the HCB detected in the melt. In the two tests, 2B and 3B,

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*Additional details on the analytical results are discussed in Appendix C.

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where the melt was analyzed, the DEs were 6-9's and 5-9's, respectively. The HCB contribution from the melt was not significant in Test 2B; however, it was significant in Test 3B since 10 times as much HCB from the feed was found in the melt than in the off-gas. It is postulated that the HCB in the melt of this last test was a result of contamination, since it is extremely unlikely that any organic material could survive in such an environment. The destruction efficiency in Sampling Location 2 would be the same as that in Location 1 since the HCB contribution from the melt far exceeded that from the stack gas from Test 3B.

Chlordane Destruction--

Destruction and Removal Efficiency--The DRE's measured at Sampling Location 1 were 6-9's or greater except for Test 1 in which the DRE was 99.99983. Thus, the salt melt was very effective in producing an off-gas substantially free of chlordane even at a melt temperature as low as 896°C (1645°F) where the DRE was 7-9's (Test 4) and even when the test was conducted at an off-specification condition such as 74% of stoichiometric air where the DRE was also 7-9's (Test 3).

The DREs measured at Sampling Location 2 were, except for the last two tests, at least two orders of magnitude greater than those measured at Sampling Location 1. The DRE values were greater than 7-9's for Tests 1 and 3 and were greater than 8-9's in Tests 2A, 2B, and 4. The greater DREs in Sampling Location 2 than in Location 1 were a result of removal of particulates by the baghouse and/or settling out of particulates in the pipes.

Destruction Efficiency--No chlordane was detected in the melt in any of the tests. However, in the case of the last three tests, the detection limit was much higher than in the first two tests. In the last three tests, there was a considerable amount of background noise due to interference by some material in the melt. The analytical method for analysis of the off-gas was not sufficiently developed to deal with this problem for melt analysis. It is not clear why this problem suddenly occurred after the first two runs. The effect of this problem was to reduce the lower limit of the DE to 99.9970.

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99.9961, and 99.9985 for Tests 2B, 3, and 4, respectively. In the case of Tests 1 and 2A, the DEs were 99.99981 and 99.999937%, respectively, and were not significantly different from the corresponding DRE's.

GC-MS Results--

The samples that were analyzed by GC-MS are shown in Table 26. Some of these samples represented some of the worst cases, where the DREs were the lowest based on the GC-EC analyses. The reconstructed ion chromatograms (RIC) for these samples are shown in Figures 14 through 18.

Figure 14 shows the RIC for the melt taken before the HCB or chlordane destruction tests. The peak occurring at Scan 910 is the d_{10}-anthracene (internal standard) peak. It was not possible to obtain good mass spectra for the relatively small peaks occuring at other scan numbers.

TABLE 26

SAMPLES ANALYZED BY GC-MS

Melt Before HCB or Chlordane Destruction Tests
Melt From HCB Test 3B
Off-Gas at Sample Location 1 of Chlordane Test 1
Off-Gas at Sample Location 1 of Chlordane Test 2B
Baghouse Dust

Figure 15 shows the RIC for the concentrated extract of 54.9 g of melt after the last HCB test (3B). The peak at Scan 858 is that of HCB at about 103 g per ml of concentrated extract.* The peak at Scan 909 is the internal standard peak. The HCB concentration in the melt determined by GC-MS (0.095 ppmw) is in excellent agreement with that of 0.10 ppmw obtained by GC-EC analysis.

---

*The 1-ml methylene chloride extract used for the GC-EC analysis was evaporated to dryness and 50-μl of methylene chloride were added to dissolve the residue. One μl of this solution contained 103 ng/μl. Thus, the 54.9 g of melt contained 5.15 μg HCB.

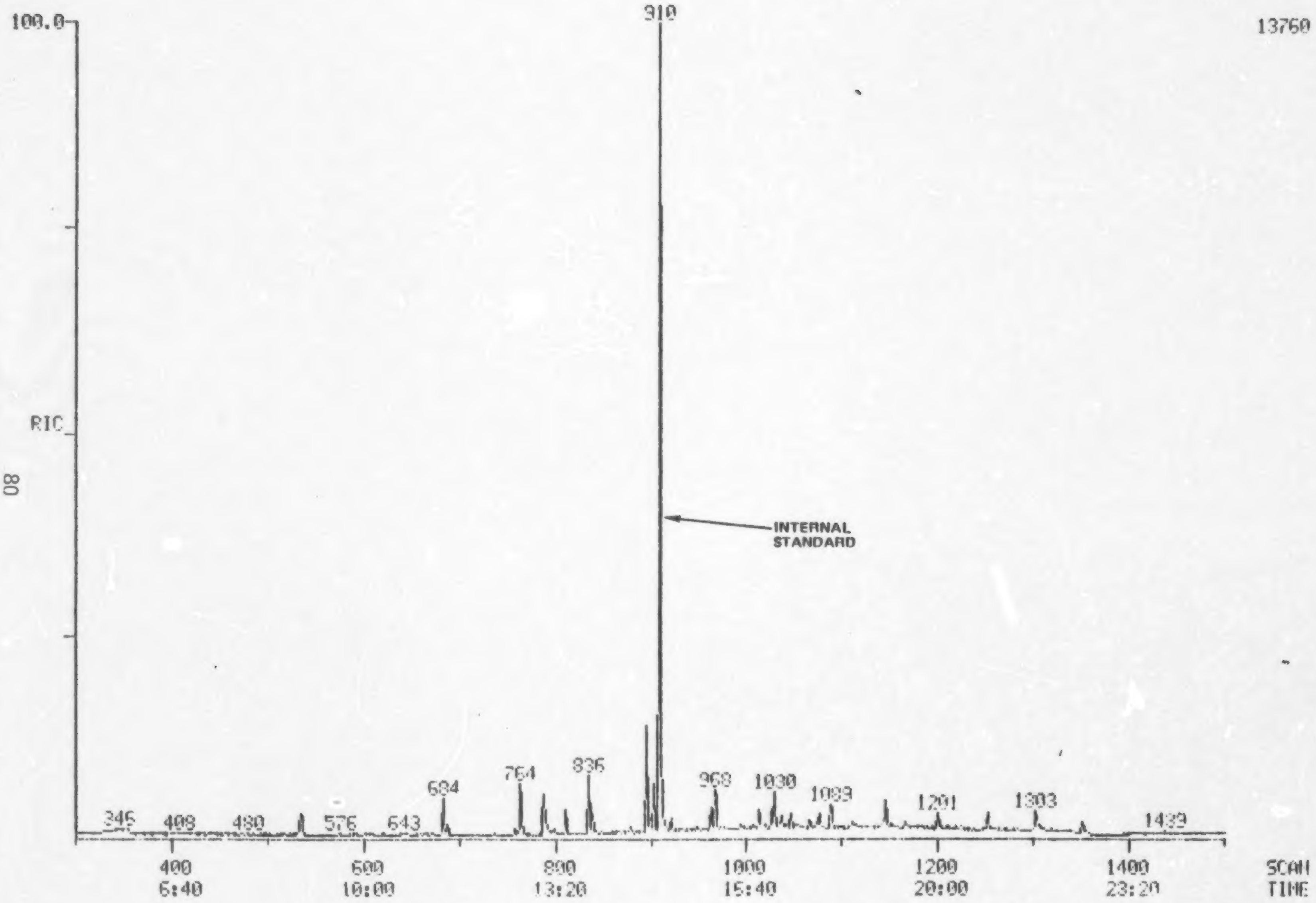

Figure 14. Ion chromatogram of melt before destruction tests

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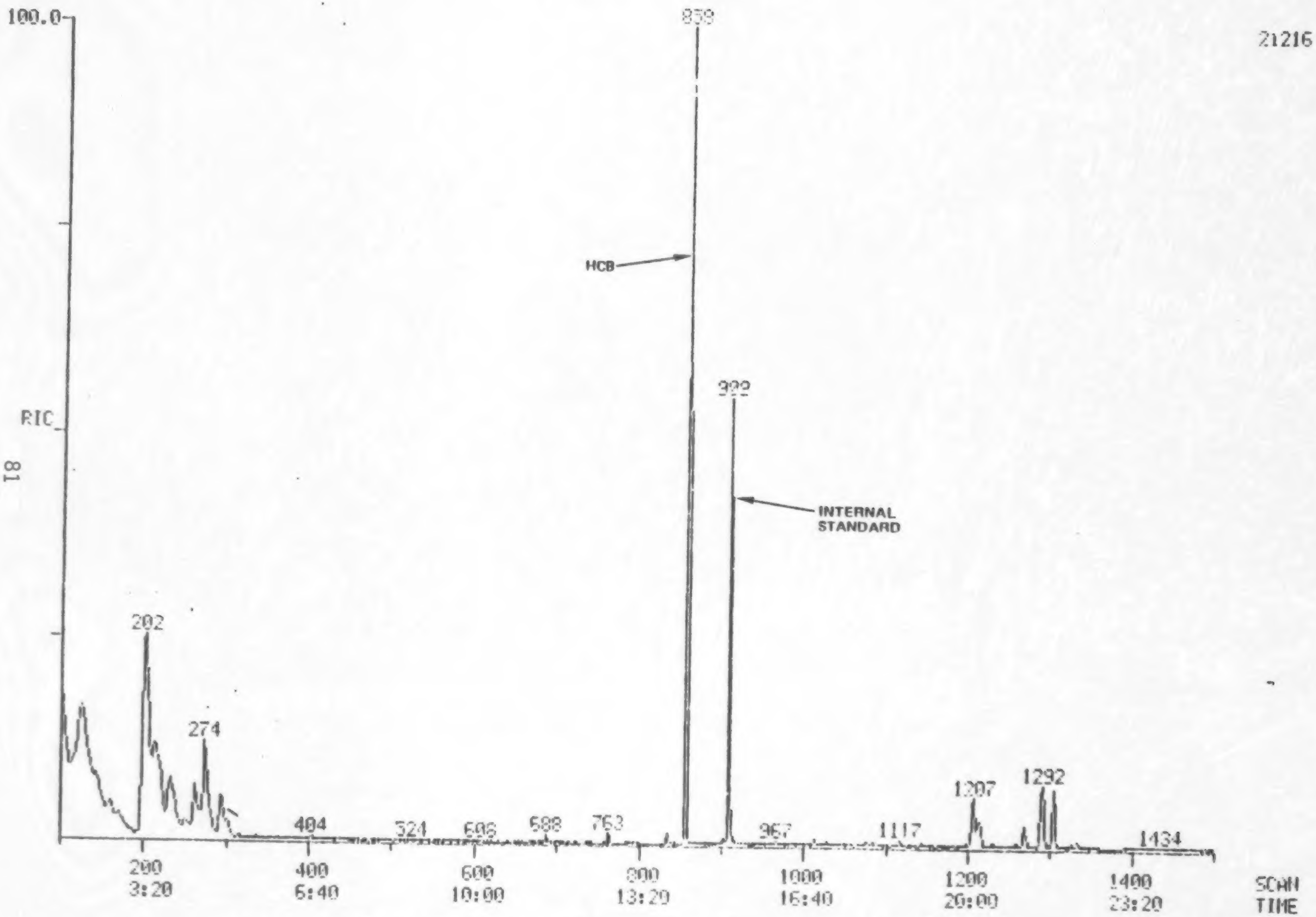

Figure 15. Ion chromatogram of melt from HCB Test 3B

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Figures 16 and 17 show the RICs for the off-gas from chlordane Tests 1 and 2B, respectively. The samples were taken at Sample Location 1. No chlordane was found in either test. The peaks in Figure 17 were examined qualitatively. Scans 864 and 914 were substituted alkyl benzene and the rest of the peaks occurring from Scans 689 through Scan 1303 were hydrocarbons C_{15} through C_{25}. Their concentrations were estimated to be ~20 μg per μl of concentrated solvent.

Figure 18 shows the RIC from baghouse dust. The peak occurring at Scan 908 is the internal standard peak. Neither HCB nor chlordane were detected in this sample. Peaks at Scan 1120 and the peak just prior to 1120 could not be identified due to poor mass spectra fit to NBS library spectra.

Off-Gas Compositions

The off-gas composition for the HCB and chlordane tests are shown in Tables 27 and 28, respectively. The NO_x values were very low, $\leq$125 ppm, except in the first chlordane test where the NO_x concentration was 630 ppm. No explanation can be given for this high value. The concentrations of unburned hydrocarbons were also very low, in all cases but one being less than 100 ppm. The CO concentrations as in the bench-scale tests were higher than those corresponding to a combustion efficiency of 99.9%. However, as in the bench-scale tests, there is no correlation between CO concentrations and destruction efficiencies.

Three measurements of HCl concentrations were made near Sampling Location 1 with Drager tubes. These were conducted during chlordane Tests 1, 2A, and 3. The HCl concentrations were <100 ppm. As in the bench-scale tests, blanks conducted when no chlorinated material was being fed also showed about the same concentration as when chlorinated material was fed. Thus, NaCl probably affects the Drager tube measurements of HCl. The impingers downstream of the baghouse were analyzed for acid by titration. No acid was detected. Thus, no detectable HCl was emitted into the stack.

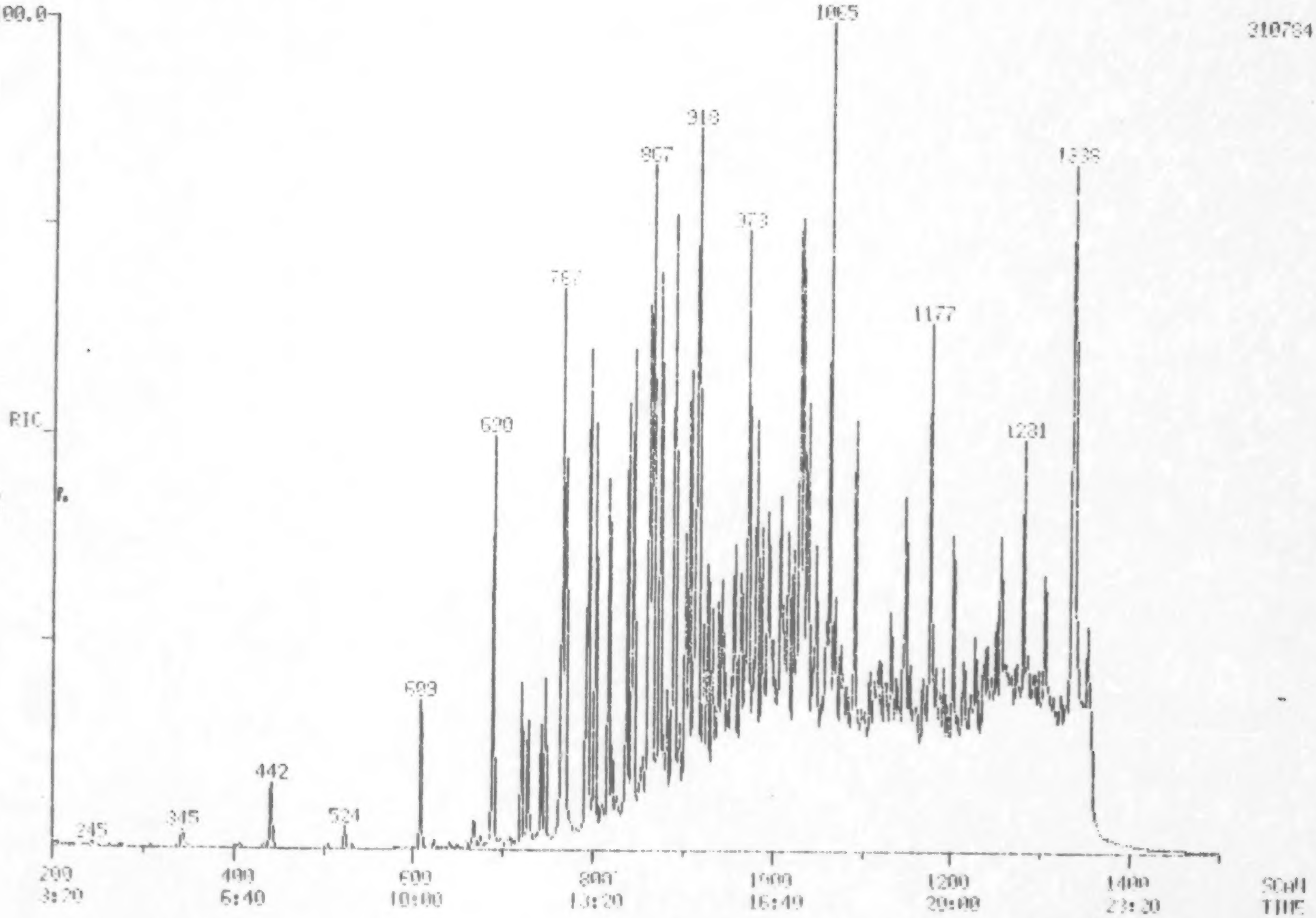

Figure 16. Ion chromatogram of off-gas from Chlordane Test 1

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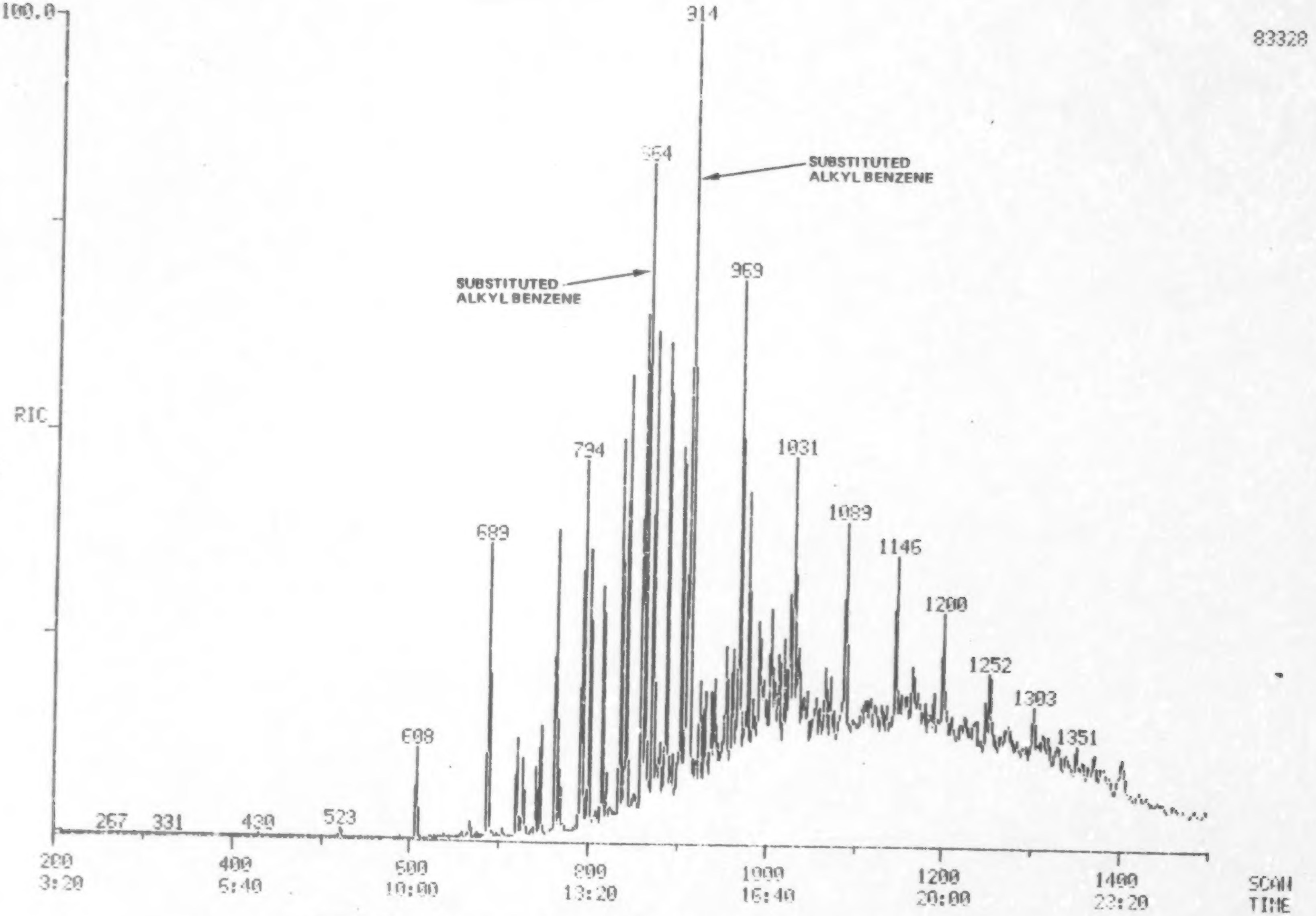

Figure 17. Ion chromatogram of off-gas from Chlordane Test 2B

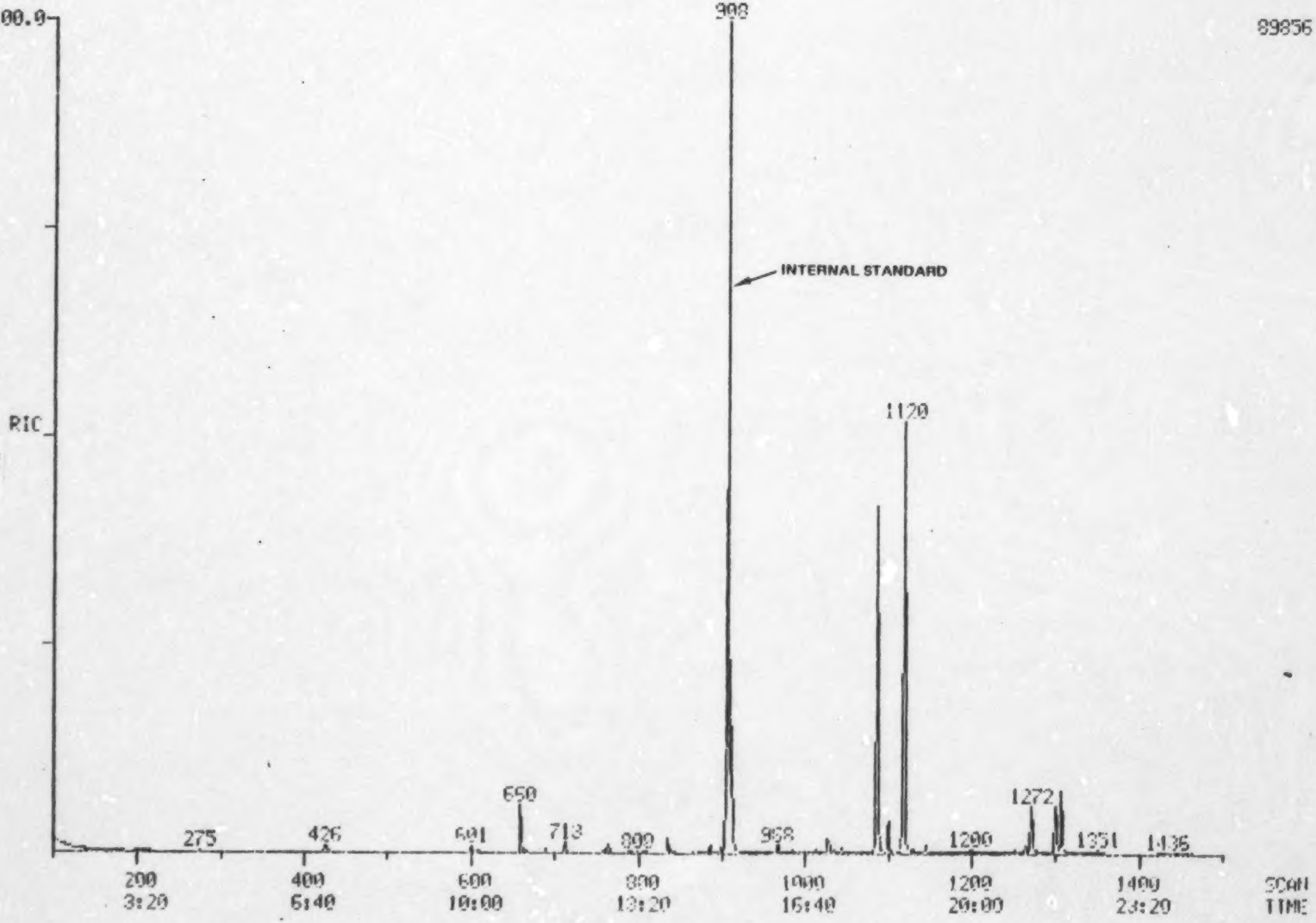

Figure 18. Ion chromatogram of baghouse dust

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TABLE 27

OFF-GAS COMPOSITION FROM HCB PILOT-SCALE DESTRUCTION TESTS

Test No.	Off-Gas Composition[b]								Combustion Efficiency (%)	Particulate Loading mg/m^3
	Volume %					(ppmv)				
	O_2	Ar	N_2	CO_2	CO	HCl	NO_x	HC		
1	5.2	0.9	77.7	15.9	0.31	NA[a]	NA[a]	0	98.1	6.2
2A	2.8	0.9	81.7	14.6	0.12	NA	125	NA	99.2	NM[c]
2B	9.9	0.9	80.1	8.8	0.32	NA	70	NA	96.5	107
3A	4.8	0.9	76.2	16.3	2.1	NA	125	110	88.6	NM[c]
3B	5.3	0.9	72.4	18.8	2.6	NA	80	35	87.9	31

[a] NA — Not analyzed
[b] Measured at Sampling Location 2
[c] Not measured

TABLE 28

OFF-GAS COMPOSITION FROM CHLORDANE PILOT-SCALE DESTRUCTION TESTS

Test No.	Off-Gas Composition[a]								Combustion Efficiency (%)	Particulate Loading mg/m^3
	Volume %					(ppmv)				
	O_2	Ar	N_2	CO_2	CO	HCl	NO_x	HC		
1	4.3	0.9	79.3	15.5	0.06	<100	630(?)	20	99.6	15
2A	4.0	0.9	79.5	15.4	0.23	<100	0.5	1.0	98.5	13
2B	8.5	0.9	80.4	10.3	0.04	NM	7.3	0.4	99.6	18
3	1.0	0.8	75.4	18.5	3.7	<100	15.7	60	83.3	4.1
4	5.1	0.9	80.7	12.9	0.41	NM	7.2	NA	96.9	8.6

[a] Measured at Sampling Location 2

The particulate loadings downstream of the baghouse (Sampling Location No. 2) were very low (<50 mg/m^3).

DISPOSAL OF SPENT SALT

The HCB and chlordane concentrations in the spent salt were <1 ppm. At these low concentrations, the salt can be disposed of as a non-hazardous material. However, its solubility in water requires that this salt be disposed of in a controlled manner.

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SECTION 8

COMPARISON OF BENCH-SCALE AND PILOT-SCALE TEST RESULTS

It is of interest to the evaluation of the program results to compare the bench-scale tests with those of the pilot-scale tests. A comparison of the destruction results is given first, followed by a comparison of the combustion efficiencies.

DESTRUCTION RESULTS

6-1/2"

A comparison of the extent of waste destruction achieved in the bench-scale and in the pilot-scale tests was made to determine (1) the extent of correspondence of the two tests and (2) the destruction enhancement, if any, due to the deeper bed in the pilot-scale destructor vessel. In order to make a meaningful comparison, it was important to examine the destruction at similar operating conditions. This was accomplished by comparison of the results of the off-gas samples taken at Sampling Location 1 of the pilot-scale facility with those of the off-gas samples from the bench-scale tests. Thus, the waste removal achieved in the downstream piping and in the baghouse of the pilot facility were excluded from the comparison. Values of DRE only were compared because (1) melt samples (needed for DE values) were measured in only two of the five pilot-scale tests with HCB and (2) the detection limits of the melt sample, in three of the five pilot-scale tests, were excessively high to permit a meaningful comparison.

9-1/8"

HCB

The bench-scale and pilot-scale DRE results are given in Table 29. The off-spec bench-scale test (No. 5) and the 800°C bench-scale test (No. 4) were not included in this comparison because no pilot-scale tests were conducted at corresponding conditions. Two sets of comparable data are presented. The

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first set is at the higher temperatures of 958-1004°C and with excess air. The second set is at lower temperatures (902 and 918°C) and also with excess air. In all cases, the DREs were 6-9's or greater. At the higher temperature (the first set of values), the bench-scale test, (2), at 1004°C exhibited better destruction (7-9's 86) than the pilot-scale test, 3B at 985°C (6-9's 80), about the same destruction as the pilot-scale tests 3A at 985°C (>8-9's 18) and 2A at 958°C (>7-9's 87) and less destruction than the pilot-scale test 1 at 969°C (8-9's 59) in which no HCB was detected. At the lower temperature (the second set of values), the DREs for the bench- and pilot-scale tests were essentially the same. It therefore can be concluded that in general the two HCB bench-scale tests (2 and 3) and the pilot-scale tests yielded approximately the same destruction results with no apparent destruction enhancement in the pilot-scale unit.

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TABLE 29

DESTRUCTION AND REMOVAL EFFICIENCY OF HCB[a]

Normal Condition	Facility	Test No.	Temp. (°C)	% of Stoich. Air	Destruction and Removal Efficiency (%)
Higher Temp. Excess Air	Bench	2	1004	118	7-9's 86
	Pilot	3B	985	151	6-9's 80
	Pilot	3A	982	120	>8-9's 19[b]
	Pilot	1	969	135	8-9's 59
	Pilot	2A	958	140	>7-9's 87[b]
Lower Temp. Excess Air	Bench	3	902	127	6-9's 78
	Pilot	2B	918	141	6-9's 74

[a] Pilot-scale values at Sampling Location 1

[b] >denotes "not detected"; DREs may have been greater

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Chlordane

The bench-scale and pilot-scale DRE results are given in Table 30. Three sets of comparable data are presented. The first set is at the higher temperature 961-999°C and with excess air. The second set is at the lower temperatures (896-933°C) and also with excess air. The third set is at the higher temperature (991 and 1002°C) but with deficient air (74 and 81% of stoichiometric air) representing the off-specification test conditions.

TABLE 30

DESTRUCTION AND REMOVAL EFFICIENCIES OF CHLORDANE[a]

Normal Condition	Facility	Test No.	Temp. (°C)	% of Stoich. Air	Destruction and Removal Efficiency (%)
Higher Temp. Excess Air	Bench	2	999	121	>6-9's 51[b]
	Pilot	1	982	103	5-9's 83
	Pilot	2A	961	116	6-9's 55
Lower Temp. Excess Air	Bench	3	898	118	>6-9's 03
	Pilot	4	896	138	7-9's 34
	Pilot	2B	933	123	6-9's 32
Higher Temp. Deficient Air	Bench	4	1002	81	>4-9's 34[b]
	Pilot	3	991	74	7-9's 47

[a] Pilot-scale values at Sampling Location 1

[b] >denotes "not detected"; actual DREs may have been greater

At the higher temperatures and with excess air (the first set of data), the bench-scale test 2 at 999°C exhibited greater destruction (>6-9's 51) than the pilot-scale test 1 at 982°C (5-9's 83) and about the same as the pilot-scale test 2A at 961°C (6-9's 55). (If the chlordane detection limit had been lower in the bench-scale test, the bench-scale destruction possibly would have been greater than that of the pilot-scale test 2A.) At the lower temperatures and with excessive air (the second set of data), the comparison is made difficult because the chlordane detection limit in the bench-scale test yielded a DRE of >6-9's 03. While the DRE was large, this value was less than those of the pilot-scale tests 4 at 896°C (7-9's 34) and 2B at 933°C (6-9's 32). At

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the higher temperature but with deficient air, the comparison is again made difficult because of the high chlordane detection limit. As stated earlier, the peaks observed in the bench-scale test 4 by GC-EC were identified by GC-MS as not due to chlordane isomers. Thus, no firm conclusion can be drawn for this third set of data. It is probable, however, that the destruction in the pilot-scale test was greater than that in the bench-scale test because GC-EC chromatograms of the off-gas from the former contained less organic material than did the off-gas from the latter.

Thus, the bench-scale DRE was at times better and at times worse than that of the pilot-scale DRE. However, the difference between the bench-scale and pilot-scale results was sufficiently small such that it can be concluded that within the variability of the corresponding sets of test conditions that actually existed, the bench-scale tests predicted the excellent destruction demonstrated in the pilot-scale tests.

COMBUSTION EFFICIENCY*

The carbon monoxide emissions were shown, at least in the case of chlordane bench-scale tests, to be highly dependent on temperature and stoichiometry. Thus, in making a comparison of the combustion efficiencies from the off-gas composition, it was important to compare the bench-scale and pilot-scale results at similar temperatures and at similar stoichiometries. However, in order to compare the off-gas compositions, it was first necessary to determine if the off-gas compositions from both types of destructors were consistent with those calculated from the waste and air feed rates, assuming complete reaction of the waste with sodium carbonate.

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*The combustion efficiency is defined as the following ratio:

$$\frac{\%\ CO_2}{\%\ CO_2 + \%\ CO}$$

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The reaction of a chlorinated hydrocarbon waste, $C_cH_hC\ell_\ell$ with Na_2CO_3 and air is given by

$$C_cH_hC\ell_\ell + \frac{\ell}{2} Na_2CO_3 + \left(\frac{4c + h - \ell}{4}\right) O_2$$

$$\frac{h}{2} H_2O + \ell NaC\ell + \left(\frac{2c + \ell}{2}\right) CO_2$$

The above assumes that no CO is formed. The off-gas composition (CO_2, O_2, and N_2 + Ar) on a dry basis can be calculated from the waste feed rate, the air feed rate, and the composition of the waste. However, when CO is present in the gas, the reaction of the waste is given by

$$C_cH_hC\ell_\ell + \frac{\ell}{2} Na_2CO_3 + \left(\frac{4c + h - \ell - 2xc}{4}\right) O_2$$

$$\frac{h}{2} H_2O + NaC\ell + xCO + \left(\frac{2c + \ell - 2xc}{2}\right) CO_2$$

In order to calculate the CO_2, O_2, and N_2 + Ar concentrations as well as other parameters from the waste and air feed rates, the experimental CO concentrations must be included in the calculations. The derivation for the equations used for the calculated results in this section is given in Appendix B.

The CO_2, O_2, and N_2 + Ar compositions (on a dry basis) were calculated using Equations 2, 3, and 5, respectively, in Appendix B.* The percent of stoichiometric air was calculated in two ways. The first was with Equation 1 (Appendix B) which is based on the air and waste feed rates. The second was with Equation 11 which is based on the observed O_2 and CO concentrations in the off-gas. The carbon balance was calculated with Equation 15 and multiplied by 100 to give the result in percentage form. These parameters for all the bench-scale and pilot-scale tests using excess air were calculated and the results are shown in Table 31.

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*The definitions of the symbols in the equations of Appendix B are given in the first page of Appendix B. Equation 9 was also used in the calculations to take into account the result of CO being present in the off-gas.

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TABLE 31

CALCULATED VS OBSERVED GAS COMPOSITIONS FOR BENCH-SCALE AND PILOT-SCALE TESTS

Facility	Feed	Test No.	Temp. (°C)	% CO	Comp. of Off-Gas (Vol %)						% of Stoichiometric Air		
					CO_2		O_2		N_2 + Ar		From Feed Rates	Calc. From Gas Comp.	Carbon Balance (%)
					Calc	Obs	Calc	Obs	Calc	Obs			
Bench	HCB	2	1004	1.3	19.6	18.6	3.8	3.1	75.7	76.3	118.4	114.0	95.5
Bench	HCB	3	902	2.2	17.1	16.9	5.4	4.3	75.3	75.9	127.5	119.1	99.1
Bench	HCB	4	803	2.4	19.5	15.6	3.3	7.1	74.7	75.1	111.3	141.7	82.5
Bench	Chlordane	2	999	0.04	13.5	13.7	4.3	3.8	81.1	83.1	124.6	121.1	100.6
Bench	Chlordane	3	898	1.2	12.7	13.2	4.4	3.5	81.8	82.4	121.1	115.4	103.7
Pilot	HCB	1	969	0.31	16.3	15.9	5.4	5.2	77.9	78.6	134.6	131.9	94.7
Pilot	HCB	2A	958	0.12	15.9	14.6	5.9	2.8	79.0	82.6	140.1	115.2	85.4
Pilot	HCB	2B	918	0.32	16.9	8.8	6.0	9.9	76.9	81.0	140.7	190.6	48.0
Pilot	HCB	3A	982	2.1	18.8	16.3	4.3	4.8	74.9	77.1	120.1	123.0	82.9
Pilot	HCB	3B	985	2.6	21.6	18.8	7.5	5.3	68.3	73.3	150.6	128.8	82.0
Pilot	Chlordane	1	982	0.06	18.8	15.5	0.6	4.3	80.6	80.2	102.7	125.2	80.8
Pilot	Chlordane	2A	961	0.23	16.6	15.4	3.1	4.0	80.2	80.4	116.1	122.4	88.0
Pilot	Chlordane	2B	933	0.04	16.0	10.3	3.9	8.5	79.9	81.3	122.6	166.5	61.0
Pilot	Chlordane	4	896	0.41	13.9	12.9	6.1	5.1	79.7	81.6	138.2	129.9	90.0

The bench-scale results show very good agreement between the calculated and observed off-gas compositions (within about 1%) except for HCB Test 4 conducted at 800°C. The percent of stoichiometric air values calculated from the feed rates agreed quite well with those calculated from the observed O_2 and CO content of the off-gas except for HCB Test 4. The carbon balance exceeded 95% except for HCB Test 4.*

The agreement between the observed and calculated off-gas compositions was not as good in the pilot-scale tests as it was in the bench-scale tests. The same applies to the percent of stoichiometric air values. In addition, the carbon balance was not as good in the pilot-scale tests. Of the HCB tests, Test 1 showed the best agreement in both the off-gas compositions and in the percent of stoichiometric air values as well as the carbon balance. Of the chlordane tests, Test 4 showed the best agreement. The CO_2 results were in poor agreement in HCB Test 2B and in Chlordane Test 2B. The oxygen results were in poor agreement in the HCB Tests 2A, 2B, and 3B, and Chlordane Tests 1 and 2B. The percent of stoichiometric air values agreement was poor in the same tests as those in which the oxygen concentrations showed poor agreement. The better agreement in the case of the bench-scale results was presumably due to the better control of the waste feed rate in the smaller unit which resulted in a more constant gas composition.

The combustion efficiencies of both bench-scale and pilot-scale tests were compared for tests in which excess air was used. Because of the disparities of the two sets of stoichiometric values, averages of these values were used. The results for HCB and chlordane are shown in Tables 32 and 33, respectively. A discussion of these comparisons is presented below.

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*The carbon balance for the two bench-scale tests conducted in the off-spec conditions was 93.4% for HCB Test 5, and 99.5% for Chlordane Test 4.

TABLE 32

COMBUSTION EFFICIENCIES OF HCB

Nominal Conditions	Facility	Test No.	Temperature (^oC)	% of Stoichiometric Air	Vol % CO_2[a]	Vol % CO[a]	Combustion Efficiency %
Higher Temperatures	Bench	2	1004	116	18.6	1.3	93.5
	Pilot	3B	985	140	18.8	2.6	87.9
	Pilot	3A	982	122	16.3	2.1	88.6
	Pilot	1	969	133	15.9	0.31	98.1
	Pilot	2A	958	128	14.6	0.12	99.2
Lower Temperatures	Bench	3	902	123	16.9	2.2	88.5
	Pilot	2B	918	166	8.8	0.32	96.5

[a] Experimental values

TABLE 33

COMBUSTION EFFICIENCIES OF CHLORDANE

Nominal Conditions	Facility	Test No.	Temperature (^oC)	% of Stoichiometric Air	Vol % CO_2[a]	Vol % CO[a]	Combustion Efficiency %
Higher Temperatures	Bench	2	999	123	13.7	0.04	99.7
	Pilot	1	982	114	15.5	0.06	99.6
	Pilot	2A	961	119	15.4	0.23	98.5
Lower Temperatures	Bench	3	898	118	13.2	1.2	91.7
	Pilot	2B	933	145	10.3	0.04	99.6
	Pilot	4	896	134	12.9	0.41	96.9

[a] Experimental values

HCB

The 800°C bench-scale Test 4 was not included in this comparison because no pilot-scale test was conducted at this temperature. Two sets of comparable data are presented in Table 32. The first set is at the higher temperatures of 958-1004°C; the second set is at lower temperatures (902 and 918°C).

At the higher temperatures (the first set of values), the combustion efficiency (93.5%) of the bench-scale Test 2 was higher than those of the pilot-scale Tests 3B and 3A (87.9 and 88.6%, respectively), but was lower than those of the pilot-scale Tests 1 and 2A (98.1 and 99.2% at 969 and 958°C, respectively). At the lower temperature, the combustion efficiency of the bench-scale test (88.5%) was lower than that of the pilot-scale test (96.5%).

Chlordane

Again, two sets of comparable data are presented. At the higher temperature, the combustion efficiency of the bench-scale Test 2 (99.7%) was about the same as that of the pilot-scale Test 1 (99.6%) and was greater than that of the pilot-scale Test 2A (98.5%) conducted at a somewhat lower temperature (961°C). At the lower temperatures, the combustion efficiency of the bench-scale Test 3 (91.7%) was lower than those of the two pilot-scale Tests 2B and 4 (99.6 and 96.9, respectively).

COMPARISON SUMMARY

Overall, it appears that the agreement in DREs between the bench-scale unit and the pilot-scale test is sufficiently good when compared at similar temperatures that confidence can be placed in the bench-scale tests for predicting the performance of larger scale MSD units. At lower temperatures of about 900°C, the combustion efficiencies of the pilot-scale unit were greater than that of the bench-scale unit. However, at the higher temperature of about 1000°C, they were comparable.

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SECTION 9

PLANT SCALE-UP AND ECONOMICS

ENGINEERING STATUS

Reference Commercial System Design

The conceptual design of a commercial MSD plant capable of 908 kg/h (2000-lb/h) throughput for liquid PCBs has been completed. The plant is also capable of destroying other chlorinated liquid and solid wastes. The rated throughput is based upon the use of oxygen-enriched air feed. Design modifications may be needed on a case-by-case basis after evaluation of waste feed characteristics. Figures 19 and 20 are a schematic drawing and engineering concept of this plant, respectively.

The commercial plant employs three metal destructor modules. Each destructor vessel, which is 1.4-m diameter and 7.0-m high (54 in. and 23 ft, respectively), contains a bed of molten salt at a nominal operating temperature of 940°C (1725°F). The vessel's outer cylindrical surfaces are finned in order to provide heat transfer surface for heat rejection. Blowers force air over the finned surfaces to remove excess heat generated by combustion of the waste. The upper, insulated, off-gas region of the vessel provides additional volume for disengagement of salt from the off-gas, entry to the ducting to the baghouse, and a seat for the vessel lid. The off-gas resulting from the combustion process is cleaned of particulates in a baghouse and subsequently vented through an exhaust stack.

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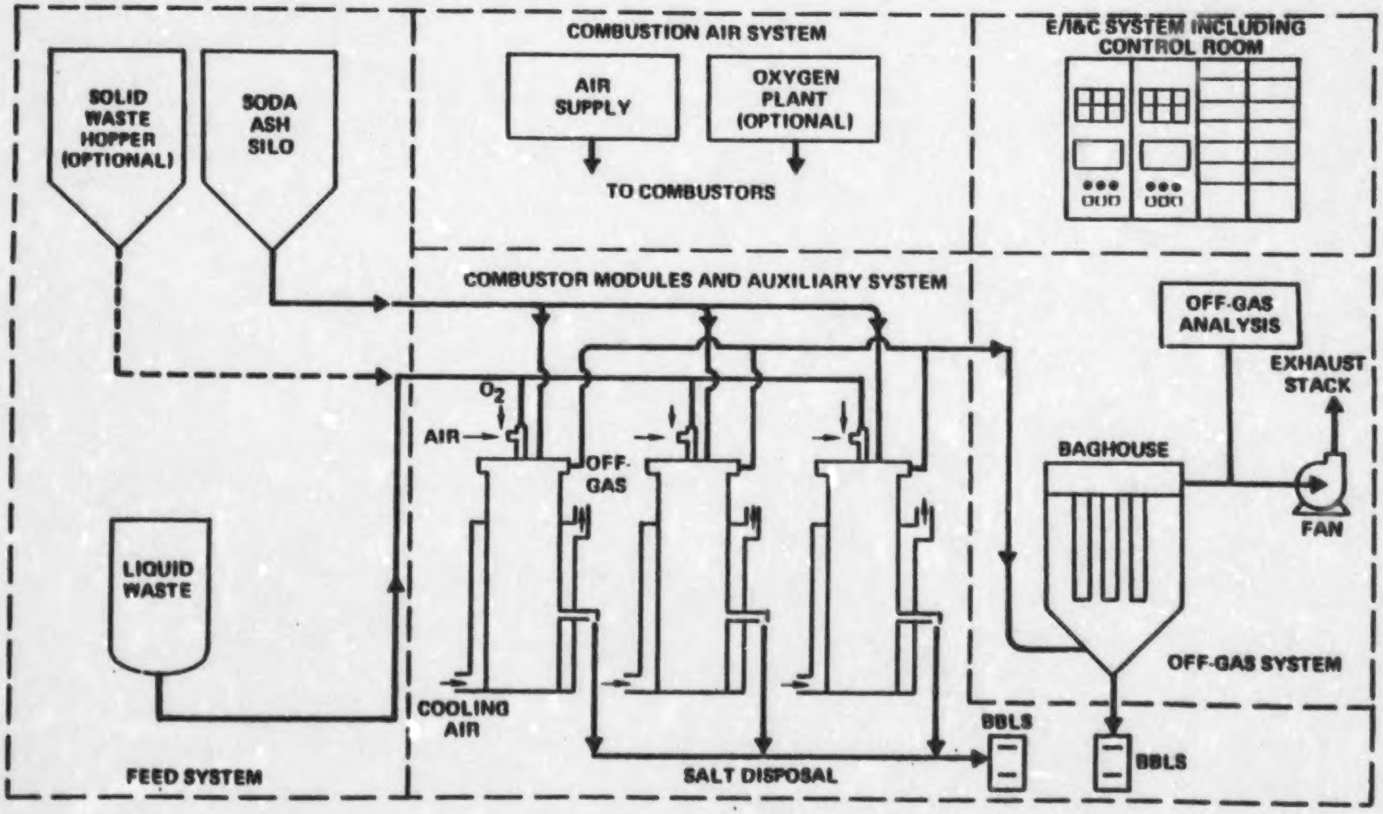
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Figure 19. Simplified MSD plant schematic

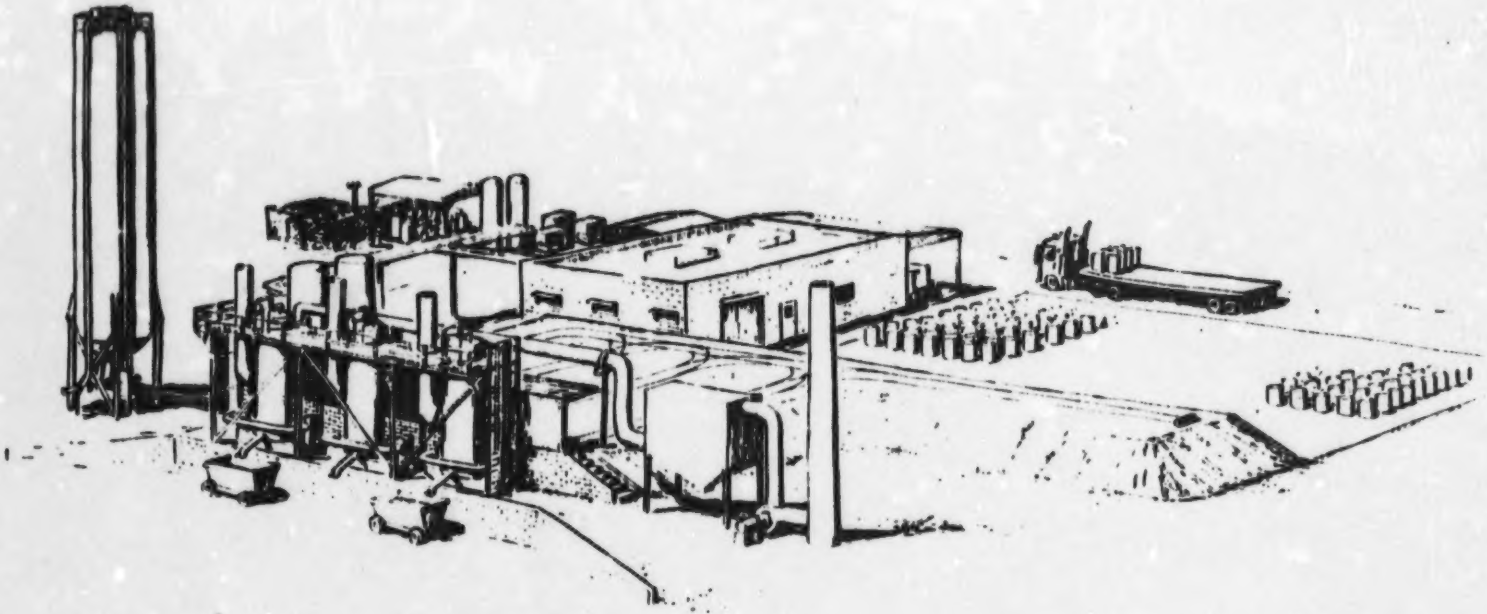

Figure 20. Artist's rendition of MSD plant

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Sodium carbonate (soda ash), waste, and combustion air are injected beneath the surface of the melt through downcomers supported by the vessel lid. An overflow line is welded to the side of the vessel. The outlet of the overflow line is heated to prevent salt freezing and plugging. Continuous overflow, in proportion to the volume of injected soda ash, occurs during MSD plant operation. Auxiliary ports for liquid level instruments and working access are also provided in the lid.

The destructor vessel is operated at a slightly negative pressure to preclude ambient release of hazardous waste feed through the melt withdrawal piping in the event of an upset condition in which the feed directly enters the off-gas region as a result of feed-tube failure. This condition is extremely unlikely due to design safeguards which involve double containment of the waste feed. Several design approaches to overall system controls and safeguards are currently under consideration. The selection of the commercial plant control and engineered safety systems will be based upon acceptable public and personnel safety requirements.

Transportable System Design

The conceptual engineering has been completed on a scaled prototype transportable version of the commercial plants. This concept employs a single metal combustor with a reduced-size vessel (same height but 5/8 the diameter of the large vessel). All other features of the system are essentially the same as the reference commercial plant except they are reduced in size or capacity to be consistent with the 102-kg/h (225-lb/h) throughput capacity of the combustor. This system is also designed for operation with or without oxygen-enriched air-feed.

All system components can be skid mounted for portable applications. Transport would require two semi-truck trailers for combustor and process equipment plus a specially equipped van to carry special instrumentation and control room. It is anticipated that the entire facility could be located at selected sites, operated for short periods to handle specific waste destruction problems, and then would be removed. This concept eliminates costly

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handling and transportation problems related to movement of the hazardous material.

An engineering concept of the transportable MSD plant is shown in Figure 21.

MSD ECONOMICS

The MSD process for hazardous waste destruction has been successfully demonstrated through the pilot-plant stage. Cost projections have been made for commercial-scale plants based upon conceptual plant design. These cost estimates, which include engineering and construction costs, equipment costs, and operating and maintenance costs, cannot be confirmed until the first commercial plant is in operation. The plant capital cost for a 908-kg/h waste capacity is estimated at $4.0 million (1981 dollars). The associated projected operating and maintenance (O&M) costs are estimated to be $3.0 million per year. The O&M estimate includes allocations for (1) operation with oxygen-enriched air, (2) for property taxes and insurance, (3) process and supervisory labor, (4) process materials, power, and (5) periodic replacement of short-life equipment items. The latter includes waste feed downcomers (1-yr life) and the destructor vessel (2-yr life). A present value cash flow financial analysis of the MSD plant indicates that the system is competitive with rotary kiln systems designed to handle hazardous waste streams requiring wet scrubber off-gas treatment. The MSD plant should require less capital investment for a given throughput and should be less expensive to operate and maintain than a rotary kiln with equivalent waste treatment capacity in cases where the waste contains less than 20 wt % ash and are difficult to burn. Wastes fitting these requirements include chlorinated hydrocarbons.

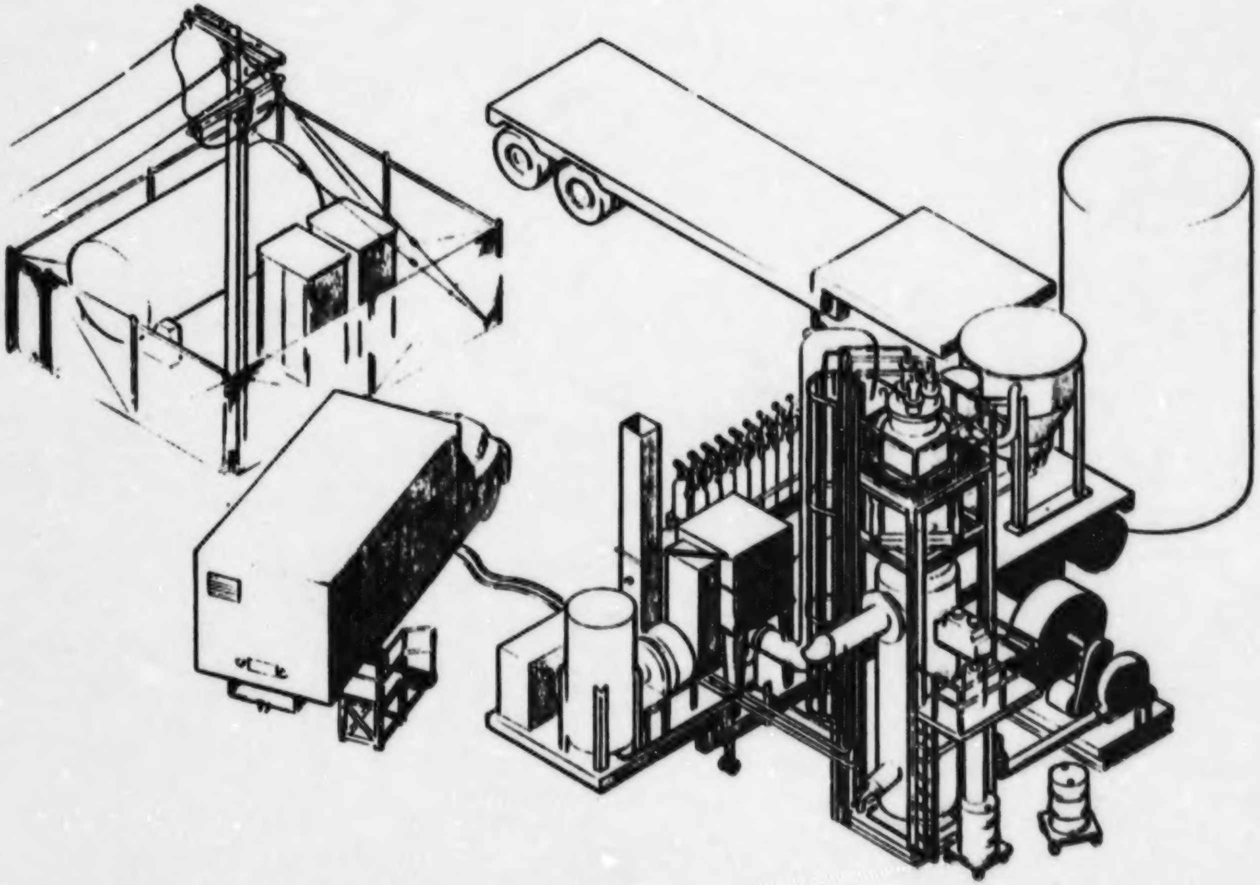

Figure 21. Artist's rendition of Transportable MSD Unit

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REFERENCES

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3. Federal Register 46, No. 15, January 23, 1981, p 7666

4. Charles L. Stratton, Stuart A. Whitlock, and Mark J. Allen, "A Method for Sampling and Analysis of Polychlorinated Biphenyls in Ambient Air," EPA-600/4-78-048 (August 1978)

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APPENDIX A

HANDLING PROCEDURE FOR HEXACHLOROBENZENE AND CHLORDANE

1. INTRODUCTION

The ability of the Molten Salt Test Facility (MSTF) to destroy aromatic organochlorides is being evaluated for the Environmental Protective Agency (EPA-Cincinnati). The first two compounds to be studied are hexachlorobenzene (HCB) and 1,2,4,5,6,7,8,8 octachloro-4,7 methano-3a,4,7,7a tetrahydroindane (chlordane). Both compounds are toxic and combustible. They require special handling to protect workers and the general public.

The success of this test program depends on our ability to measure very low levels of organic chlorides in the melt and off-gases of the MSTF. Careless handling of these materials is not only dangerous to everyones health, but also may increase the background level so high that the critical test measurements cannot be made reliably.

HCB is a crystalline solid that is slightly toxic (causes readily reversible changes which disappear after the end of exposure). It is also dangerous when exposed to heat or flame as it emits toxic fumes of chlorides. The material is received in double plastic bags and should be stored in the unbroken containers until needed. Face masks (respirators) and protective clothing should be worn during transfer of the material. In case of a spill, vacuum up* the spilled material to avoid raising dust and flush the area with water after facility management authorization.

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*The vacuum cleaner must be equipped with a high efficiency filter on its exhaust.

Chlordane is a highly toxic liquid that can cause death or permanent injury after a very short exposure to a small quantity. The liquid can be absorbed through the skin or swallowed and its vapors can be breathed. Chlordane should be stored in nonfragile containers. The material is combustible but should not be flushed with water to extinguish it. Spills should be contained, the material absorbed on a porous solid such as sawdust and swept up. The area should then be scrubbed with soap and water and the solution collected for proper disposal. Workers should wear chemical cartridge respirators and impervious clothing, i.e., rubber gloves and aprons whenever exposure is possible (i.e., during transfer and handling).

2. RECEIVING AND STORAGE

A. HEXACHLOROBENZENE (HCB)

HCB is packaged and shipped in 80-lb, double-wall bags. These unbroken bags should be stored on a pallet in a cool, dry, well-ventilated area. The area should be roped off and posted to warn of its hazards. Bags that are opened shall be repackaged in a closed container to prevent creation of an airborne hazard, and stored in the same area as the unbroken bag.

The unbroken bags and the closed containers must be labeled in a readily visible location. The labels must bear the following information:

HEXACHLOROBENZENE

COMBUSTIBLE

HARMFUL IF INHALED, SWALLOWED,
OR ABSORBED THROUGH THE SKIN

Keep away from heat, sparks, and open flames. In case of fire, use foam or dry chemical fire extinguisher.
Avoid breathing vapor.
Do not get on skin or in eyes or mouth.

Keep container closed when not in use.
Use only with adequate ventilation.

First Aid: If substance contacts skin, immediately wash affected area with soap and water. In case of eye contact, flush eye with running water for 15 minutes. If overexposure occurs, report to the Medical Department immediately.

Overexposure is defined as exposure in excess of the recommended environmental limits or any exposure, including dermal contact with substances, that results in observed effects on health.

Warning signs shall be posted in readily visible locations in or near areas where occupational exposure can occur. These signs shall read:

HAZARDOUS AREA
HEXACHLOROBENZENE
COMBUSTIBLE
HARMFUL IF INHALED, SWALLOWED,
OR ABSORBED THROUGH THE SKIN

Prevent sources of heat, sparks, or open flames. No smoking or eating permitted. In case of fire, use fire extinguishers at (location). Avoid breathing vapor. Avoid contact with skin or eyes.

If respiratory protection is required in the area, the following statement in large letters must be added to the required signs:

RESPIRATORY PROTECTION REQUIRED IN THIS AREA

If respiratory protection is needed only occasionally, separate signs, reading as above, must be posted when appropriate.

B. CHLORDANE

Chlordane is packaged and shipped in sealed 30-gallon metal drums and shall be stored in these drums until needed. The storage area shall be cool, dry, and well-ventilated. Either the area must be diked to contain any spill or the drums must be stored in secondary containers that can hold their contents. The storage area shall also be roped off and posted with warning signs.

The warning signs shall read:

HAZARDOUS AREA
CHLORDANE
COMBUSTIBLE
HARMFUL IF INHALED, SWALLOWED, OR
ABSORBED THROUGH THE SKIN

Prevent sources of heat, sparks, or open flames. No smoking or eating permitted. In case of fire, use extinguishers at (location). Avoid breathing vapors. Avoid contact with skin or eyes.

The drums shall be labeled:

CHLORDANE
COMBUSTIBLE
HARMFUL IF INHALED, SWALLOWED, OR
ABSORBED THROUGH THE SKIN

Keep away from heat, sparks, and open flames. In case of fire, use fog or water spray or foam on dry chemical fire extinguisher. Avoid breathing vapor. Do not get on skin or in eyes or mouth. Keep container closed when not in use. Use only with adequate ventilation.

First Aid: If substance contacts skin, immediately wash affected area with soap and water. In case of eye contact, flush eye with running water for 15 minutes. If overexposure occurs, report to the Medical Department immediately.

Overexposure is defined as exposure in excess of the recommended environmental limits or any exposure, including dermal contact with substances, that result in observed effects on health.

If respiratory protection is required in the area, the following statement in large letters must be added to the required signs:

RESPIRATORY PROTECTION REQUIRED IN THIS AREA

If respiratory protection is needed only occasionally, separate signs, reading as above, must be posted when appropriate.

3. EQUIPMENT NEEDS

While working with HCB and chlordane, workers who have had any contact with waste materials will need clean coveralls each day and should shower after every work shift. Used coveralls must be disposed of or thoroughly laundered in an approved manner before reuse. Rubber gloves, rubber aprons, rubber or plastic boots, goggles, and appropriate respirators are required while handling or transferring either material. The appropriate respirator for use with HCB airborne concentrations up to 18 ppm is a chemical cartridge with a high efficiency particulate filter. For chlordane, a NIOSH-approved chemical cartridge for pesticides should be used.

Personnel monitoring will be conducted at the operators breathing zone during transfer of either material or whenever a potential for significant personnel exposure exists. Monitoring may also be required at other times until the atmospheric contamination has been reduced to a safe level.

Tanks, hoppers, and other containers used for storage of HCB or chlordane shall be sealed except when transferring material. They must also be boxed or diked to contain the contents in the event of a spill.

Pipe, fittings, and all equipment should be leak-tight. Joints that cannot be made leak-tight must be enclosed.

The time-weighted average exposure limit for HCB is 1.0 mg/m^3 and for chlordane, the threshold limit value (TVL) is 0.5 mg/m^3. If either of these limits is approached or suspected, respirators must be worn in the area until the source has been located and sealed and the contaminant level returns to a safe value.

4. HANDLING DURING TEST

The bags of HCB and drums of chlordane will be transported on pallets by forklift. The forklift operator shall wear a lapel monitor and coveralls. The bags of HCB shall be moved close to the MSTF hopper to minimize handling, and the drums of chlordane shall be placed as close to the liquid injector tank as possible.

During loading of the hopper with HCB or pumping of chlordane into the liquid injector tank, workers are required to wear coveralls, rubber apron, rubber gloves, rubber or plastic boots, goggles, and respirator. The breathing zones will be monitored. All unnecessary personnel will be cleared from the area.

HCB will be loaded into the MSTF hopper by hand carrying the 80-lb bags to the hopper, one at a time, opening the hopper lid, slowly emptying the bag, closing the hopper lid, and placing the bag in a closed waste container. Care should be taken to avoid raising dust. This container should be labeled the same as the hexachlorobenzene bags and disposed of as specified in Section 8.

After each bag is loaded, allow time for the visible dust to settle before loading a second bag. Partly emptied bags should be placed in a sealed container, identified, and stored in the same area as the unbroken bags.

Chlordane will be transferred from the 30-gallon drums to the liquid injector tank by using a hand-operated barrel pump placed in the drum. The empty drums will be resealed and stored as contaminated waste and disposed of as specified in Section 8. Partially filled drums shall be resealed and stored in the designated storage area.

The Facility Emergency Plan for Building 5 shall be updated to include response to an HCB or chlordane spill. The reentry team shall be trained to handle evacuation, to fight fires that produce toxic fumes, and to clean up spills.

Protective Services and Health and Safety shall be notified immediately in the event of any accidental spills or unplanned handling event not covered by this procedure.

5. SANITATION

Clothing used in the HCB or chlordane work areas shall be worn one day only and then sent to an approved laundry for decontamination or disposal. Workers exposed to these materials shall shower at the end of each work shift before putting on street clothes.

Preparing, dispensing (including vending machines), storing, and consumption of food and beverages shall be prohibited in HCB and chlordane work areas. Workers who handle HCB or chlordane shall be instructed to wash their hands thoroughly with soap and water before eating, smoking, or using toilet facilities.

6. FIRES

Both HCB and chlordane are combustible materials that emit toxic fumes of chlorides when burned. Protective clothing--particularly self-contained respiratory protection--must be donned before attempting to fight any fire involving either of them. The fire should be fought from an upwind position.

Use either foam, dry powder, or CO_2 fire extinguishers in a manner to minimize scattering or dispersing the materials. Do NOT use water to fight the fire.

Once the fire is extinguished, clean up the area using the procedure for a spill as described in Section 8.

7. MONITORING AND RECORD KEEPING

A survey shall be made prior to testing to determine the background level of HCB and chlordane in the work area. The survey shall be repeated during testing of each material and after shutdown of the tests.

A program of personnel monitoring, using lapel monitors to sample the workers' breathing zones supplemented with area monitoring, shall be conducted during the testing. Sufficient number of samples shall be taken to characterize the workers' exposure during each work shift. If any monitor indicates airborne concentrations in excess of $1.0\ mg/m^3$ for HCB or $0.5\ mg/m^3$ for chlordane, workers will be required to wear respirators until the concentration returns to a safe level.

Records of personnel exposure and medical surveillance shall be kept in accord with the record-keeping requirements of OSHA and federal, state, and local regulations. Employees shall be able to obtain information on their own work place environmental exposures.

Pertinent medical records shall be retained by the employer for 30 years after employment has ended. Records of environmental exposures applicable to an employee shall be included in his or her medical records. These medical records shall be made available, upon request, to the designated medical representatives of the Secretary of Labor, of the Secretary of Health, Education, and Welfare, of the employer, and of the employee or former employee. These personnel records must comply with the record-keeping requirements of OSHA.

8. WASTE HANDLING

A. HEXCHLOROBENZENE

If HCB is spilled, the powder should be immediately vacuumed up* and placed in a closed metal waste storage drum along with the cleaning materials. The workers involved in the cleanup should remain upwind of the spill. The area should then be flushed with a large quantity of water after facility management authorization. This water should be collected and soaked up on an absorbent material such as sawdust, then placed in closed metal waste containers and sent to an approved site for burial. No liquid waste shall be released to the Santa Susana Field Laboratory waste water system.

All the waste that can be fed to the MSTF should be destroyed in it. Those solid wastes that cannot be burned in the MSTF should be stored in closed metal containers. When filled, these containers shall be disposed of in an approved manner per SOP K-18.

B. CHLORDANE

If chlordane is spilled, it should be soaked up with an absorbent such as sawdust or it should be diked to contain the spill until it can be soaked up.

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*The vacuum cleaner must be equipped with a high efficiency filter on its exhaust.

The chlordane-soaked material, the dike, and any other loose material that contacted the chlordane should be swept up and placed in a closed metal waste container. All rags, mops, and other materials contaminated with chlordane should also be stored in a closed metal container. Workers should remain upwind of the spill. The area should then be scrubbed with soap and water, the solution collected in drums, soaked up on an absorbent, and disposed of in an approved manner per SOP K-18.

All wastes that can be fed to the MSTF should be burned in it. Those wastes that cannot be burned in the MSTF should be stored in closed metal containers. When filled, the metal containers shall be disposed of in an approved manner per SOP K-18.

C. MELT

Melt from the MSTF may have residual concentrations of HCB and/or chlordane and related compounds, and should be treated as contaminated until analysis proves otherwise. Therefore, workers handling the melt shall follow the precautions as defined by Paragraph 4 for handling during test. During the test, the melt will be drained into metal drums. After the test, the melt will be drained into a drain cart, solidified, and then stored in sealed metal drums. If chemical analysis shows the level of HCB or chlordane exceeds the allowable limits, the drums shall be disposed of in an approved manner per SOP K-18. If analysis shows acceptably low levels, the salt may be disposed of in a normal manner.

APPENDIX B

DERIVATION OF EQUATIONS USED TO CALCULATE OFF-GAS COMPOSITIONS AND OTHER PARAMETERS

DEFINITION OF SYMBOLS

The symbols used below are defined as:

a = feed rate of combustible material (kg/h)
g = fraction of material that is C, H, and Cℓ
b = feed rate of gas (sm^3/h)*
S = percent of stoichiometric air
M = formula weight of material that contains C, H, and Cℓ (kg/mole)
n = number of moles per hour
P = concentration of gaseous species (vol %)
T_o = standard temperature (°K)*
c, h, ℓ = number of carbon, hydrogen, and chlorine in Formula $C_cH_hC\ell_\ell$
x = fraction of carbon atoms converted to CO
$\phi = (4c + h - \ell)/4$**
$\theta = (2c + \ell)/2$**

DERIVATION

The material to be processed has a hazardous component with the empirical formula:

$$C_cH_hC\ell_\ell$$

1. Reaction of $C_cH_hC\ell_\ell$ with O_2 and Na_2CO_3

The reaction of $C_cH_hC\ell_\ell$ with O_2 and Na_2CO_3 is:

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*The standard temperature for b and T_o in most cases is 294.2°K

**When the chemical reaction involving 1 mole of $C_cH_hC\ell_\ell$ with O_2 and Na_2CO_3 is balanced, ϕ is the number of moles of O_2 reacted and θ is the number of moles of CO_2 produced.

$$C_cH_hC\ell_\ell + \frac{\ell}{2} Na_2CO_3 + \left(\frac{4c + h - \ell - 2xc}{4}\right) O_2$$

$$\longrightarrow \frac{h}{2} H_2O + \ell NaC\ell + xcCO + \left(\frac{2c + \ell - 2xc}{2}\right) CO_2$$

2. Flow Rate of O_2 and Unreactive Gases

We process a kg/h of material which contains g fraction of $C_cH_hC\ell_\ell$. This corresponds to ag/M moles/h of $C_cH_hC\ell_\ell$, where M is the formula weight (kg/mole) of $C_cH_hC\ell_\ell$. We do this by passing b standard cubic meters/hr (sm^3/h) of air into the melt. Since air contains 21.0% oxygen, this is equivalent to passing 0.210b sm^3/h oxygen into the melt. Accompanying this oxygen is b-0.210b = 0.790b sm^3/h of nitrogen plus argon.

The number of gram moles of O_2/h, $\dot{n}_{O_2}$, which is passed into the melt is given by the ideal gas law

$$\dot{n}_{O_2} = \frac{P\dot{V}_{O_2}}{RT_o} = \frac{(101,300)(0.210b)}{(8.314)\ T_o}$$

where $\dot{V}_{O_2}$ is the flow rate of oxygen in the inlet gas (sm^3/h) and T_o is the temperature (K) at standard conditions. P, in this case, is the pressure in Pascals and is 101,300 Pascals (1 atm) and R is the gas constant (J/K mole).

$$\dot{n}_{O_2} = 2559b/T_o$$

$$\dot{n}_{(N_2+Ar)} = 9627b/T_o$$

3. Stoichiometric Conditions

Stoichiometric conditions are defined as those at which all the oxygen reacts and forms only CO_2 and H_2O. Under such conditions, the ag/M moles/h of $C_cH_hC\ell_\ell$ will consume $\frac{ag}{M}\left(\frac{4c + h - \ell}{4}\right)$ moles/h of O_2 and will produce $\frac{ag}{M}\left(\frac{2c + \ell}{2}\right)$ moles/h of CO_2.

Let $\phi = (4c + h - \ell)/4$ and $\theta = (2c + \ell)/2$.

Thus ag/M moles/h of $C_cH_hC\ell_\ell$ will consume $ag\phi/M$ moles/h of O_2 and produce $ag\theta/M$ moles/h of CO_2 under stoichiometric conditions (no CO formed).

4. Flow Rate of Unreacted Oxygen

The flow rate of unreacted O_2 is that of the total inlet oxygen minus that of the oxygen consumed

$$\frac{2559b}{T_o} - \frac{ag}{M}\left(\frac{4c + h - \ell}{4} - \frac{2xc}{4}\right) = \frac{2559b}{T_o} - \frac{ag}{M}\left(\phi - \frac{xc}{2}\right)$$

5. Percent Stoichiometric Air

The percent stoichiometric air, S, is $100 \dfrac{\text{(Flow rate of oxygen in inlet gas)}}{\text{(Flow rate of stoichiometric oxygen)}}$

$$S = 100\left(\frac{2559b/T_o}{ag\phi/M}\right)$$

$$\boxed{S = 100 \frac{2559bM}{T_o ag\phi}} \qquad (1)$$

6. CO_2 Concentration as a Function of b/a

Let P_{CO_2} = vol % CO_2. It is assumed in these and succeeding calculations that all the H_2O is condensed before it reaches the gas analyzer. Thus, the gas concentrations are on a dry basis.

$$P_{CO_2} = \frac{100\,\dot{n}_{CO_2}}{\dot{n}_{CO_2} + \dot{n}_{CO} + \dot{n}_{\text{unreact } O_2} + \dot{n}_{(N_2+Ar)}}$$

$$P_{CO_2} = \frac{100\left(\frac{ag\theta}{M} - \frac{agxc}{M}\right)}{\frac{ag\theta}{M} - \frac{agxc}{M} + \frac{agxc}{M} + \frac{2559b}{T_o} - \frac{ag\phi}{M} + \frac{agxc}{2M} + \frac{9627b}{T_o}}$$

Divide numerator and denominator by ag/M,

$$\boxed{P_{CO_2} = \frac{100(\theta - xc)}{\theta - \phi + \frac{12190\ bM}{T_o ag} + \frac{xc^*}{2}}} \qquad (2)$$

7. O_2 Concentration as a Function of b/a

Let P_{O_2} = vol % O_2

$$\boxed{P_{O_2} = \frac{100\ \frac{2559bM}{T_o ag} - \phi + \frac{xc}{2}}{\theta - \phi + \frac{12,190bM}{T_o ag} + \frac{xc}{2}}} \qquad (3)$$

8. P_{CO} as a Function of b/a

$$\boxed{P_{CO} = \frac{100(xc)}{\theta - \phi + \frac{12,190bM}{T_o ag} + \frac{xc}{2}}} \qquad (4)$$

9. P_{N_2+Ar} as a Function of b/a

$$\boxed{P_{N_2+Ar} = \frac{100\left(\frac{9627bM}{T_o ag}\right)}{\theta - \phi + \frac{12,190bM}{T_o ag} + \frac{xc}{2}}} \qquad (5)$$

10. Percent Stoichiometric Air as a Function of P_{O_2} and P_{CO}

From Equation (1)

$$S = 100\left(\frac{2559bM}{T_o ag\phi}\right)$$

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*xc in this and in the remaining equations is due to the CO observed in the off-gas and is calculated by Equation 9 which expresses xc in terms of the observed CO concentration.

$$\frac{2559}{T_o ag} = \frac{\phi S}{100} \tag{6}$$

$$\frac{12,190}{T_o ag} = \frac{\phi S}{21.0} \tag{7}$$

Substitute Equations 6 and 7 into Equation 3.

$$P_{O_2} = \frac{100\left[\frac{\phi S}{100} - \phi + \frac{xc}{2}\right]}{\theta - \phi + \frac{\phi S}{21} + \frac{xc}{2}} \tag{8}$$

From Equation 4

$$P_{CO} = \frac{100\ xc}{\theta - \phi + \frac{12,185bM}{T_o ag} + \frac{xc}{2}}$$

$$100xc = P_{CO}\,\frac{xc}{2} + P_{CO}\left(\theta - \phi + \frac{12,190bM}{T_o ag}\right)$$

$$\boxed{xc = \frac{P_{CO}\left(\theta - \phi + \frac{12,190bM}{T_o ag}\right)}{100 - \frac{P_{CO}}{2}}} \tag{9}$$

Substitute Equation 8 into Equation 10.

$$\frac{xc}{2} = \frac{\frac{P_{CO}}{2}\left[\theta - \phi + \phi S/21\right]}{100 - \frac{P_{CO}}{2}} \tag{10}$$

Substitute Equation 10 into Equation 8.

$$P_{O_2} = \frac{100\left[\frac{\phi S}{100} - \phi + \frac{P_{CO}}{2}\,\frac{(\theta - \phi + \phi S/21)}{100 - P_{CO}/2}\right]}{\theta - \phi + \frac{\phi S}{21} + \frac{P_{CO}}{2}\left[\frac{\theta - \phi + \phi S/21}{100 - P_{CO}/2}\right]}$$

Simplifying

$$P_{O_2} = \frac{100\phi S - 10{,}000\phi + 1.88\phi S P_{CO} + 50\theta P_{CO}}{100\theta - 100\phi + 4.76\phi S}$$

Solving for S

$$\boxed{S = \frac{100 + \left(\frac{\theta}{\phi} - 1\right) P_{O_2} - \frac{\theta}{\phi}\,\frac{P_{CO}}{2}}{1 - 0.0476\,P_{O_2} + 0.0188\,P_{CO}}} \qquad (11)$$

11. Carbon Balance

Obtain flow rate of off-gas (b_{off}) on basis of a N_2 balance, i.e., the flow rate of N_2 in the inlet gas equals the flow rate of N_2 in the off-gas.

$$\dot{n}_{N_2\text{-in}} = \dot{n}_{N_2\text{-out}}$$

$$b_{off} = \frac{P_{N_2\text{-in}}\,b}{P_{N_2\text{-out}}} \qquad (12)$$

Let $\dot{w}$ be the flow rate of carbon in the form of CO and CO_2 in the off-gas (kg/h).

$$\dot{w}_{C\text{-out}} = 12\left(\dot{n}_{C\text{ from }CO_2} + \dot{n}_{C\text{ from }CO}\right)$$

Where 12 is the atomic weight of carbon (kg/mole^{-1})

$$\dot{w}_{C\text{-}out} = .012\left(\frac{P_{CO_2}\, b_{off}}{RT_o} + \frac{P_{CO} b_{off}}{RT_o}\right) = \frac{12P_T b_{off}}{RT_o}\left(P_{CO_2} + P_{CO}\right) \qquad (13)$$

where P_T is the total pressure.

Substituting Equation 12 into Equation 13

$$\dot{w}_{C\text{-}out} = \frac{.012P_T bP_{N_2\text{-}in}}{RT_o P_{N_2\text{-}out}}\left(P_{CO_2} + P_{CO}\right)$$

Since P_T = 101, 300 Pascals, R = 8.314 $JK^{-1}mole^{-1}$

$$\dot{w}_{C\text{-}out} = 115.3\,\frac{b}{T_o P_{N_2\text{-}out}}\left(P_{CO_2} + P_{CO}\right) \qquad (14)$$

The flow rate of organic carbon into the salt $C_{in} = af_c + 0.169\ af_\ell = a\ (f_c + 0.169f_\ell$, where f_c and f_ℓ are the weight fraction of carbon and chlorine in the waste. The coefficient 0.169 is due to the fact that each mole of chlorine produces 1/2 mole of CO_2; thus, 35.5 kg chlorine produces 6 kg carbon. Thus, the carbon balance is given by

$$\boxed{CB = \frac{115.3\ b\left(P_{CO_2} + P_{CO}\right)}{T_o P_{N_2\text{-}out}a\ \left(f_C + 0.169f_\ell\right)}} \qquad (15)$$

APPENDIX C

ADDITIONAL DETAILS ON THE ANALYTICAL RESULTS

To support the low values of concentrations of HCB and chlordane in the off-gas and melts as well as the high destruction efficiencies, a discussion of the detection limits and the minimum detectable concentrations of these compounds in the off-gas and melts are given. Examples of calculations of the destruction and removal efficiencies are also given. The final values are given with two significant figures with the uncertainty being in the second figure.

DETECTION LIMITS AND MINIMUM DETECTABLE CONCENTRATIONS FOR HCB AND CHLORDANE

The detection limits for HCB and chlordane in various sample extracts along with minimum detectable amounts (in ng) and minimum detectable concentrations (in ng/g for melts and in mg/m^3 and ppmv for gas samples) are shown in Tables C-1, C-2, and C-3. Only the samples analyzed by the Environmental Monitoring and Services Center (EMSC) are included in these tables. Test 4 of the bench-scale HCB tests and Test 4 of the bench-scale chlordane tests were not included since the HCB or chlordane concentrations in some of the samples in these tests were very high compared to the detectable concentrations.

Column (1) shows the attenuation at which sample extracts and standards were run. The volume of sample extracts ($\mu\ell$) injected into the gas chromatograph is shown in column (2). The detection limit (ng/mℓ) is shown in column (3). For HCB, the concentration of a 0.5 cm peak at the stated injected volume and attenuation was about ten times the baseline noise level. For chlordane, the concentrations were those at which the peak ranged from 0.2 to

TABLE C-1

DETECTION LIMITS AND MINIMUM DETECTABLE CONCENTRATIONS IN BENCH-SCALE TESTS

Waste	Test	Matrix	(1) GC Attenuation	(2) Injected Vol., µℓ	(3) Detection Limit, ng/mℓ	(4) Vol. of Sample, mℓ	(5) Min. Detectable Amount, ng	(6) Weight of Melt Sample, g	(7) Min. Detectable Conc'n. in Melt, ng/g	(8) Vol. Off-Gas Samples m^3	(9) Min. Detectable Con'n. mg/m^3
HCB	All	Polyureth Plug	16	1.0	1	5.0	5	NA[d]	NA	0.087[b]	6×10^{-5}[b]
HCB	All	Filter	16	1.0	1	5.0	5	NA	NA	0.087[b]	6×10^{-5}[b]
HCB	2	Washings	16	1.0	1	5.0	5	NA	NA	0.087	6×10^{-5}
HCB	3	Washings	16	1.0	1	50	50	NA	NA	0.087	6×10^{-4}
HCB	5	Washings	16	1.0	1	90	90	NA	NA	0.025	3.6×10^{-3}
HCB	2	Impinger	16	1.0	1	140	140	NA	NA	0.087	1.6×10^{-3}
HCB	3	Impinger	16	1.0	1	140	140	NA	NA	0.087	1.6×10^{-3}
HCB	5	Impinger	16	1.0	1	140	140	NA	NA	0.025	5.6×10^{-3}
HCB	2	Melt	32	0.5	4.0	5.0	20	21	1.0	NA	NA
HCB	3	Melt	32	0.5	4.0	5.0	20	25	0.80	NA	NA
HCB	5	Melt	32	1.0	2.0	5.0	10	25	0.40	NA	NA
Chlordane	2.3	Polyureth Plug	16	1.0	60	3.0	180	NA	NA	0.086	2.1×10^{-3}
Chlordane	2.3	Filter	16	1.0	60	3.0	180	NA	NA	0.086	2.1×10^{-3}
Chlordane	2.3	Impinger	16	4.0	15	70	1,100	NA	NA	0.086	1.3×10^{-2}
Chlordane	2	Washings	8	4.0	16	17	280	NA	NA	0.086	3.3×10^{-3}
Chlordane	3	Washings	8	4.0	3	70	2,200	NA	NA	0.086	2.5×10^{-2}
Chlordane	2	Melt	16	1.0	60	3.0	180	21	8.6	NA	NA
Chlordane	3	Melt	16	1.0	60	3.1	180	25	7.2	NA	NA

[a] Not applicable.

[b] Except for Test 5, 0.025 m^3; min. detectable conc'n. = 2×10^{-4} mg/m^3.

TABLE C-2

DETECTION LIMITS AND MINIMUM DETECTABLE CONCENTRATIONS IN PILOT-SCALE TESTS (UPSTREAM OF BAGHOUSE)

Waste	Test	Matrix	(1) GC Attenuation	(2) Injected Vol., mℓ	(3) Detection Limit, ng/mℓ	(4) Vol. of Sample, mℓ	(5) Min. Detectable Amount, ng	(6) Weight of Melt Sample, g	(7) Min. Detectable Conc'n. in Melt, ng/g	(8) Vol. Off-Gas Samples m^3	(9) Min. Detectable Con'n. mg/m^3
HCB	1	Plug, filter & wash	16	1.0	1	1.0	1	NA	NA	0.089	1.1×10^{-5}
HCB	2B	Plug, filter & wash	16	1.0	1	1.0	1	NA	NA	0.098	1.0×10^{-5}
HCB	2B	Melt	16	1.0	1	1.0	20[a]	21	1.0	NA	NA
HCB	3B	Plug, filter & wash	16	1.0	1	1.0	1	NA	NA	0.027	3.7×10^{-5}
HCB	3B	Melt	16	1.0	1	1.0	20[a]	55	0.36	NA	NA
Chlordane	1	Plug, filter & wash	16	1.0	50	1.0	50	NA	NA	0.084	6.0×10^{-4}
Chlordane	2A	Plug, filter & wash	16	1.0	50	1.0	50	NA	NA	0.087	5.7×10^{-4}
Chlordane	2B	Plug, filter & wash	16	1.0	50	1.0	50	NA	NA	0.060	8.3×10^{-4}
Chlordane	3	Plug, filter & wash	16	1.0	50	1.0	50	NA	NA	0.088	5.7×10^{-4}
Chlordane	4	Plug, filter & wash	16	1.0	50	1.0	50	NA	NA	0.10	5.0×10^{-4}
Chlordane	1	Melt	16	1.0	50	1.0	200[b]	40	5.0	NA	NA
Chlordane	2A	Melt	16	1.0	50	1.0	200[b]	46	4.3	NA	NA
Chlordane	2B	Melt	16	1.0	50	1.0	35,000[c]	30	1,200	NA	NA
Chlordane	3	Melt	16	1.0	50	1.0	35,000[c]	29	1,200	NA	NA
Chlordane	4	Melt	16	1.0	50	1.0	10,000[d]	23	430	NA	NA

[a] Sample diluted 1:20.
[b] Sample diluted 1:4.
[c] Sample diluted 1:700.
[d] Sample diluted 1:200.

TABLE C-3

DETECTION LIMITS AND MINIMUM DETECTABLE CONCENTRATIONS IN PILOT-SCALE TESTS (DOWNSTREAM OF BAGHOUSE)

Waste	Test	Matrix	(1). GC Attenuation	(2) Injected Vol. μl	(3) Detection Limit, ng/m	(4) Vol. of Sample, m	(5) Min. Detectable Amount, ng^a	(6) Weight of Melt Sample, g^a	(7) Min. Detectable Conc'n. in Melt, ng/g	(8) Vol. Off-Gas Samples m^3	(9) Min. Detectable Con'n, mg/m^3(a)
HCB	1	Impinger	16	5.0	0.2	15.0	<4	NA	NA	0.68	1.5×10^{-6}
		Plug, filter & wash	16	1.0	1	1.0					
HCB	2B	Impinger	16	2.0	0.5	7.0	<5	NA	NA	0.54	1.9×10^{-6}
		Plug, filter & wash	16	1.0	1	1.0					
HCB	3B	Impinger	16	2.0	0.5	7.0	<5	NA	NA	0.51	1.7×10^{-6}
		Plug, filter & wash	16	1,0	1	1.0					
Chlordane	1	Impinger	16	1.0	50	2.0	150	NA	NA	0.49	3.1×10^{-4}
		Plug, filter & wash	16	1.0	50	1.0					
Chlordane	2A	Impinger	16	1.0	50	4.0	250	NA	NA	0.48	5.1×10^{-4}
		Plug, filter & wash	16	1.0	50	1.0					
Chlordane	2B	Impinger	16	1.0	50	4.0	250	NA	NA	0.69	3.6×10^{-5}
		Plug, filter & wash	16	1.0	50	1.0					
Chlordane	3	Impinger	16	1.0	50	5.0	300	NA	NA	0.49	6.2×10^{-4}
		Plug, filter & wash	16	1.0	50	1.0					
Chlordane	4	Impinger	16	1.0	50	6.0	350	NA	NA	0.51	6.8×10^{-4}
		Plug, filter & wash	16	1.0	50	1.0					

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[a] Contribution from both the impinger and the plug, filter, and wash.

1.0 cm at the stated injected volume and attenuation. The baseline noise level was about the same as that of HCB. Column (4) shows the final volume of extract or impinger solution or probe wash sample.

A few sample extracts contained non-analyte compounds which swamped the detector when the straight extract was run. When clean-up with florisil did not remove these interferences, the extract had to be diluted to obtain a chromatogram. These dilution factors do NOT include dilutions performed on extracts in which the concentration of HCB or chlordane exceeded the working analytical range. These dilution factors are given in a footnote in Table C-2.

The minimum detectable amount (ng) of HCB or chlordane is given in column (5). It is the product of the values given in columns (3) and (4) and the dilution factor. To illustrate, in the case of the plug, filter and ash samples from location 2 (downstream of the baghouse) from Test 3 of the chlordane pilot test series, the minimum detectable amount equals 50 ng/mℓ x 1.0 mℓ = 50 ng from the plug, filter-wash, and 50 ng/mℓ x 5.0 mℓ = 250 ng from the impinger for a total of 300 ng.

Column (6) gives the weight of the melt sample that was extracted. Column (7) gives the minimum detectable concentration of HCB or chlordane in the melt (ng/g). Column (7) is the ratio of Columns (5) and (6). To illustrate, in the case of the melt sample No. 2 from chlordane bench-scale test No. 2, the minimum detectable concentration of chlordane in the melt is 180 ng/21 g = 8.6 ng/g.

Column (8) shows the volume of off-gas sampled through the plug plus filter plus probe and impinger, if present. Column (9) shows the minimum detectable concentration of HCB or chlordane in the off-gas (mg/m^3). This value is the ratio of columns (5) and (8), multiplied by the conversion factor 1 mg/10^6 ng. To illustrate, in the case of the off-gas sample from location 1 (upstream of the baghouse) from test 1 of the HCB pilot test series, the minimum detectable concentration of HCB is $\frac{1\ \text{ng}}{0.089\ \text{m}^3} \times \frac{1\ \text{mg}}{10^6\ \text{ng}} = 1.1 \times 10^{-5}$ mg/m^3. The values given in column (9) of Table C-1 represent the minimum concentration of analyte in the off-gas attributed to the particular sample that was analyzed in the bench-scale tests. The sum of the contributions of all the samples for a given test is tabulated in Table C-4 where it is compared with the actual concentration observed in the test. The minimum concentration in ppmv of HCB or chlordane is also shown and compared with the observed value in Table C-4. The concentrations in ppmv are obtained directly from the concentrations in mg/m^3, using the ideal gas law. The relationship is given by:

$$\text{conc in ppmv} = \frac{24.5}{M}\ \text{conc in mg/m}^3,$$

where M is the molecular weight (285 for HCB and 410 for chlordane.

It is noted that some chlordane sample results expressed as "less than" a quantity were not at the analytical detection limit. Some examples are the pilot-scale chlordane tests (test 1 location 1) and test 3 (location 2); pilot-scale chlordane off-gas (plug plus filter plus probe rinse), run 1; and pilot-scale chlordane test 3 downstream of the baghouse (plug plus filter plus probe rinse). The chromatograms contained chlordane and non-chlordane peaks which could not be easily separated. Chlordane concentrations for these extracts were calculated using all the area under peaks identified as chlordane (including the nonseparable peaks which were not chlordane), and the concentration was expressed as "less than" this amount.

The minimum concentrations of HCB and chlordane in the melt are given in Table C-5 along with the observed values.

TABLE C-4

MINIMUM DETECTABLE AND OBSERVED CONCENTRATIONS OF HCB AND CHLORDANE IN OFF-GAS

Waste	Test	Sample Location	Concentration of Analyte in Off-Gas			
			mg/m^3		ppmv	
			Min. Detectable	Observed	Min. Detectable	Observed
HCB	Bench-2	NA[a]	1.8×10^{-3}	$<1.9 \times 10^{-3}$	1.5×10^{-4}	$<1.7 \times 10^{-4}$
HCB	Bench-3	NA	2.3×10^{-3}	3.3×10^{-2}	2.0×10^{-4}	2.8×10^{-3}
HCB	Bench-5	NA	9.3×10^{-3}	3.7×10^{-2}	8.0×10^{-4}	3.1×10^{-3}
Chlordane	Bench-2	NA	2.1×10^{-2}	$<2.2 \times 10^{-2}$	1.3×10^{-3}	$<1.3 \times 10^{-3}$
Chlordane	Bench-3	NA	4.2×10^{-2}	$<4.5 \times 10^{-2}$	2.5×10^{-3}	$<2.7 \times 10^{-3}$
HCB	Pilot-1	1	1.1×10^{-5}	2.7×10^{-4}	9.5×10^{-7}	2.4×10^{-5}
HCB	Pilot-2B	1	1.0×10^{-5}	2.2×10^{-2}	8.6×10^{-7}	2.0×10^{-3}
HCB	Pilot-3B	1	3.7×10^{-5}	7.1×10^{-2}	3.2×10^{-6}	6.3×10^{-3}
Chlordane	Pilot-1	1	6.0×10^{-4}	5.9×10^{-2}	3.5×10^{-5}	3.5×10^{-3}
Chlordane	Pilot-2A	1	5.7×10^{-4}	3.5×10^{-2}	3.4×10^{-5}	2.1×10^{-3}
Chlordane	Pilot-2B	1	8.3×10^{-4}	6.8×10^{-2}	5.0×10^{-5}	4.1×10^{-3}
Chlordane	Pilot-3	1	5.7×10^{-4}	5.7×10^{-3}	3.4×10^{-5}	3.4×10^{-4}
Chlordane	Pilot-4	1	5.0×10^{-4}	5.3×10^{-3}	3.0×10^{-5}	3.2×10^{-4}
HCB	Pilot-1	2	1.5×10^{-6}	$<6.0 \times 10^{-6}$	1.3×10^{-7}	$<5.2 \times 10^{-7}$
HCB	Pilot-2B	2	1.9×10^{-6}	$<2.7 \times 10^{-3}$	1.6×10^{-7}	$<2.4 \times 10^{-6}$
HCB	Pilot-3B	2	1.7×10^{-6}	1.6×10^{-4}	1.5×10^{-7}	9.4×10^{-6}
Chlordane	Pilot-1	2	1.0×10^{-4}	$<4.1 \times 10^{-4}$	6.0×10^{-6}	$<2.5 \times 10^{-5}$
Chlordane	Pilot-2A	2	1.0×10^{-4}	$<5.1 \times 10^{-4}$	6.0×10^{-6}	$<3.1 \times 10^{-5}$
Chlordane	Pilot-2B	2	7.2×10^{-5}	$<3.6 \times 10^{-4}$	4.3×10^{-6}	$<2.2 \times 10^{-5}$
Chlordane	Pilot-3	2	1.0×10^{-3}	$<4.4 \times 10^{-3}$	6.0×10^{-5}	$<2.7 \times 10^{-4}$
Chlordane	Pilot-4	2	9.8×10^{-5}	$<7.8 \times 10^{-4}$	5.9×10^{-6}	$<4.7 \times 10^{-5}$

[a] NA - Not Applicable

TABLE C-5

MINIMUM DETECTABLE AND OBSERVED CONCENTRATIONS OF HCB AND CHLORDANE IN MELT

Waste	Test	Concentration of Analyte in Melt (ppmw)[a]	
		Min. Detectable	Observed
HCB	Bench-2	0.0010	<0.0010
HCB	Bench-3	0.0008	<0.0010
HCB	Bench-5	0.0004	<0.00040
Chlordane	Bench-2	0.0086	<0.0090
Chlordane	Bench-3	0.0072	<0.0080
HCB	Pilot-2B	0.0010	0.0010
HCB	Pilot-3B	0.00036	0.10
Chlordane	Pilot-1	0.0050	<0.005
Chlordane	Pilot-2A	0.0043	<0.004
Chlordane	Pilot-2B	1.2	<1.2
Chlordane	Pilot-3	1.2	<1.2
Chlordane	Pilot-4	0.43	<0.43

[a] Also μg/g

DESTRUCTION AND REMOVAL EFFICIENCY CALCULATIONS

The destruction and removal efficiency (DRE), in percent has been defined in the text as:

$$DRE = 100 \left[\frac{W_{in} - W_{out}}{W_{in}}\right]$$

Where W_{in} is the mass feed rate of the principal organic hazardous constituent (POHC) into the thermal destructor, and W_{out} is the mass emission rate of the POHC present in the exhaust emissions.

$$DRE = 100 - 100 \frac{W_{out}}{W_{in}}$$

The first number in the last equation is not subject to any uncertainty whatsoever. All of the uncertainty in the last equation is precisely the uncertainty in W_{out}/W_{in}. Therefore, the uncertainty in DE is precisely the uncertainty in W_{out}/W_{in}. Examples illustrating this are shown in three HCB pilot tests, the data of which are shown in Table C-6. Column (9) has been written in two significant figures, which is conservative since in many cases, three significant figures would have been justifiable.

TABLE C-6

CALCULATION OF DESTRUCTION AND REMOVAL EFFICIENCY FOR HCB PILOT-SCALE TESTS LOCATION 1

Test	(1) Off-Gas Volume Sampled m^3	(2) Wt HCB in Off-Gas ng	$(3)^a$ Conc'n. HCB in Off-Gas mg/m^3	(4) Total Vol. Off-Gas m^3	$(5)^b$ W_{out} (Total HCB Emitted, mg)	(6) HCB Feed Rate mg/min.	(7) Sampling Time, min.	$(8)^c$ W_{in} (Total HCB Feed (mg)	$(9)^d$ W_{out}/W_{in}	$(10)^e$ DRE
1	0.0889	24	2.7×10^{-4}	120	3.2×10^{-2}	3.57×10^5	23.0	8.21×10^6	3.9×10^{-9}	8-9's 61
2B	0.0984	2160	2.20×10^{-2}	105	2.31	5.74×10^5	19.0	1.09×10^7	2.1×10^{-7}	6-9's 71
3B	0.0274	1940	7.08×10^{-2}	110	7.79	2.04×10^6	20.0	4.08×10^7	1.9×10^{-7}	6-9's 81

[a] $(3) = \frac{(2)}{(1)} \times 10^{-6}$

[b] $(5) = (3) \times (4)$

[c] $(8) = (7) \times (6)$

[d] $(9) = (5)/(8)$

[e] $(10) = 100 - 100\ (9)$